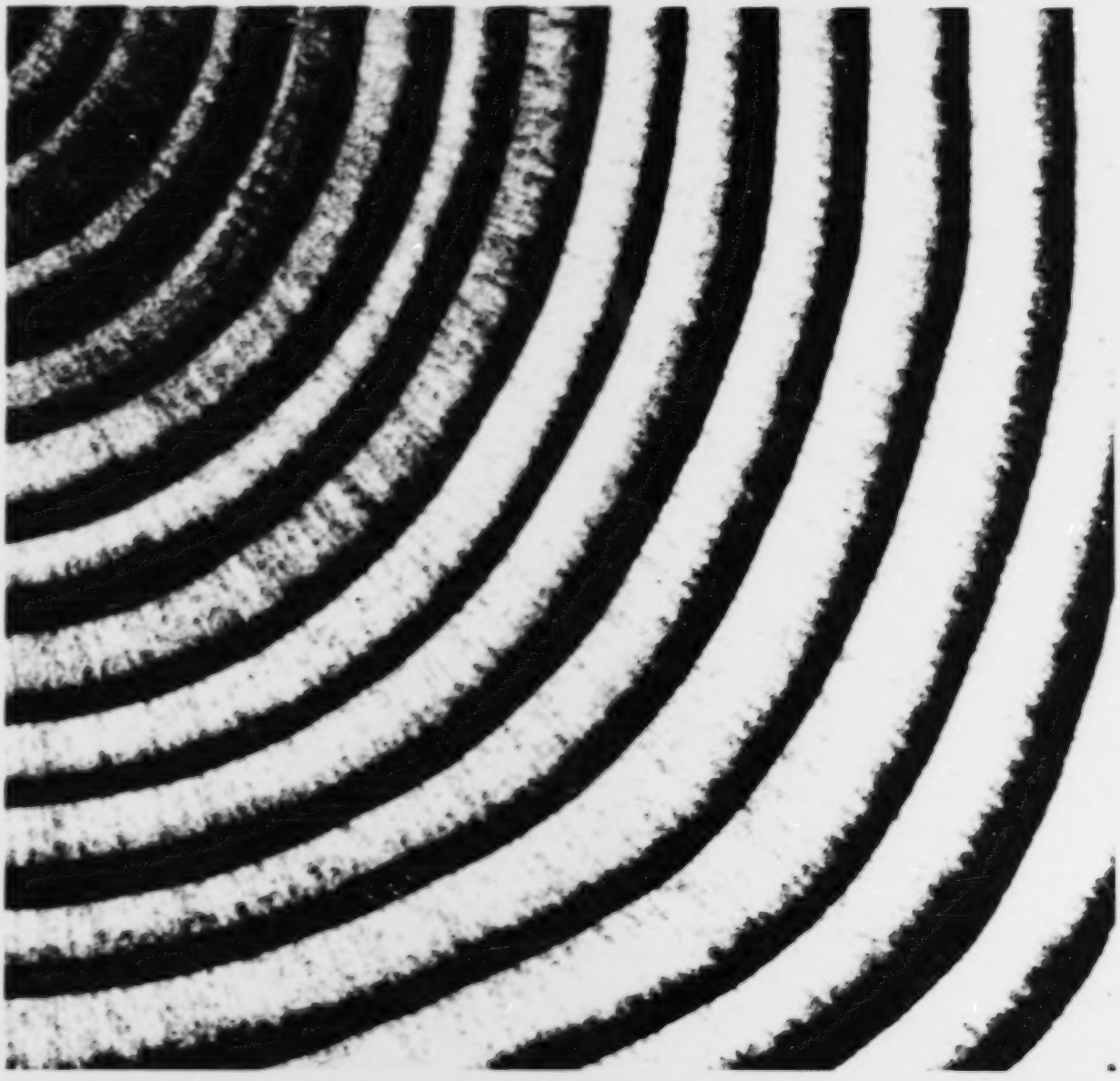
Forintek Canada Corp.

April 1989
SP-32
ISSN 0824-2119

Second Growth Douglas-Fir: Its Management and Conversion for Value

Compiled and Edited by
Robert M. Kellogg



Forintek Canada Corp. is Canada's wood products research institute providing the Canadian wood products industry and governments with services in research and development and technology transfer.

Forintek's mission is to be the leading force in the technological advancement of the Canadian wood products industry, through the creation and implementation of innovative concepts, processes, products and education programs.

Forintek Canada Corp. est l'institut de recherche sur les produits du bois du Canada. Forintek offre à l'industrie canadienne des produits du bois et aux gouvernements des services de recherche, de développement et de transfert technologique.

Forintek a comme mission d'être le chef de file du progrès technologique de l'industrie canadienne des produits du bois en créant et en mettant en oeuvre des concepts, des procédés, des produits et des programmes de formation et de perfectionnement novateurs.

Price $25.00 to non-members

Head Office and
Western Laboratory
6620 N.W. Marine Drive
Vancouver, B.C. V6T 1X2
Tel: (604) 224-3221
Fax: (604) 224-3229
Telex: 04-508552

Eastern Laboratory
800 Montreal Road
Ottawa, Ontario K1G 3Z5
Tel: (613) 744-0963
Fax: (613) 744-0903
Telex: 053-3606

Quebec Regional Office
c/o Laval University
Faculty of Forestry
P.O. Box 2208
Quebec City, Quebec G1K 7P4
Tel: (418) 656-3494
Telex: 051-31621

Edmonton Regional Office
#104 - 11710 Kingsway
Edmonton, Alberta T5G 0X5
Tel: (403) 454-2803
Fax: (403) 455-0505

SECOND GROWTH DOUGLAS-FIR: ITS MANAGEMENT AND CONVERSION FOR VALUE

A Report of the
Douglas-Fir Task Force

Compiled and Edited by
Robert M. Kellogg
Task Force Coordinator

April 1989

Forintek Canada Corp.
6620 N.W. Marine Drive
Vancouver, B.C. V6T 1X2
Telephone (604) 224-3221

Special Publication No. SP - 32

ISSN # 0824-2119

90-03918/

ACKNOWLEDGEMENTS

As coordinator of the Douglas-Fir Task Force it is my pleasure to recognize, on behalf of the Task Force, the contribution made to the successful completion of this large cooperative research effort by many individuals, the cooperating forest products companies, and the British Columbia Ministry of Forests.

The Task Force as a working group was made up of the nine project leaders and representatives of what was at the offset, six coastal forest products companies. The project leaders were as follows:

Forintek Canada Corp. Ray Clarke, Les Jozsa, Graham Mackay, Gerry Middleton and John Ruddick

Pulp and Paper Research Institute of Canada John Hatton

Ministry of Forests Ken Mitchell

Faculty of Forestry, University of British Columbia Dave Barrett and Mario Di Lucca

The cooperating companies as well as the individuals representing them that made essential contributions to the Task Force were as follows:

Canadian Pacific Forest Products Bruce Devitt, Ed Vermiere and Charlie Schwan

Canadian Forest Products Paul Wooding

Fletcher Challenge Canada Ltd. Don McMullan, Jack Toovey, Laurin Haines, John Johnson and Larry Promnitz

MacMillan Bloedel Jan Aune, Neil Brett-Davies and Phil Cottell

Western Forest Products John Barker.

Field foresters from these same companies providing invaluable assistance in locating study stands and assisting in the field work in numerous ways were:

Ken Donkersley, Brad Laughlin, Gordy Burton, Ron Elder,
Steve Lorimer, Jack Lavis and Gary Skabeikis.

Ministry of Forests staff providing guidance, critical evaluation and technical support were:

Keith Illingworth, Dave Coffey, Bill Howard, Jim Goudie, Tom Niemann, Dale Geils,
and members of the scaling service staff from Duncan, B.C.

In addition to those individuals whose contribution is recognized by authorship of chapters within this report, the following Forintek employees assisted the Task Force effort in various ways:

Economics and Marketing Gilles Brunette and Al Howatson

Research and Development Ray Clarke, Janet Ingram, Sandy McIntyre, Dave Minchin,
George Rosenberg, Al Ross, Gary Troughton, Don Walser, Dal Wright and
Students from Malaspina College.

Wood Engineering Roy Abbott, Bill Deacon, Henley Fraser, Anna Hejja, Jules Gardy,
Len Stroh and Rolley Wakeman

Wood Science Janice Macdonald, Josefina S. Gonzalez and Arlene Sawadsky

Library Barbara Holder and Marion Johnson.

Support Services Debbie Hourihane, Sung Van and Beverley Britton

Special thanks are due to Beverley who did the word processing and Sung who was responsible for graphics and design. Together these two individuals were responsible for all aspects of report production.

The following Pulp and Paper Research Institute of Canada employees made important contributions to the work carried out by that organization:

Phil Allen, Bruce Allison, Barry Christie, Maurice Douek, James Drummond, Wai Gee, Emil Koller, Alexandra Kwong, Raj Seth and Tim Stephens.

Several individuals made important contributions under contract as follows:

Howard Leach, Halco Software Systems - SAWSIM modifications.

Dave Ormerod and Seth Wilson, Sylvametrics - Development of FANSY.

Robert Macdonald, Ramsoft Systems - Graphic presentations of SYLVER results.

Tirthankar Bose - Editorial work on this report.

Harry Bardal - Graphics assistance and mechanical assembly.

Appreciation is expressed to the many individuals in industry and government who either evaluated FANSY or reviewed the original draft of the Task Force Report.

In acknowledging the contribution of individuals to a large effort like this there is a virtual certainty that someone will be overlooked. To that person, my apologies and, a special word of thanks.

R.M. Kellogg

Task Force Coordinator

April, 1989

TABLE OF CONTENTS

ACKNOWLEDGEMENTS			i
PART I:		**INTRODUCTION**	1
PART II:		**CHARACTERIZING THE RESOURCE**	
Chapter	1	**Relative Density** - L.A. Jozsa, J. Richards and S.G. Johnson	5
	2	**Juvenile-Mature Wood Transition** - C.M. Di Lucca	23
	3	**Longitudinal Shrinkage** - J.R. Nault	39
	4	**Fiber Length** - E.A. Hamm	44
	5	**Strength and Stiffness of Dimension Lumber** - J.D. Barrett and R.M. Kellogg	50
	6	**Chemical Properties** - E.P. Swan, J.R. Nault, C.R. Daniels and J.A. Cook	59
PART III:		**CONVERTING THE RESOURCE - SOLID WOOD**	
Chapter	7	**Log and Lumber Yields** - G.R. Middleton & B.D. Munro	66
	8	**Kiln Drying Lumber** - J.F.G. Mackay	75
	9	**Heartwood Treatability** - J.N.R. Ruddick	78
PART IV:		**CONVERTING THE RESOURCE - PULP**	
Chapter	10	**Density and Chemical Properties of Juvenile, Mature and Top Wood** - J.V. Hatton and K. Hunt	80
	11	**Unbleached Kraft Pulps** - J.V. Hatton and K. Hunt	87
	12	**Refiner Mechanical Pulps** - J.V. Hatton and S.S. Johal	114
PART V:		**MANAGING THE RESOURCE**	
Chapter	13	**Silvicultural Treatments and End-Product Value** - K.J. Mitchell, R.M. Kellogg and K.R. Polsson	130
PART VI:		**CONCLUSIONS AND RECOMMENDATIONS**	168
APPENDIX I:		**DOUGLAS-FIR LOG GRADES**	171

PART I: Introduction

The forest industry in Canada will become increasingly dependent on managed second-growth timber for its wood supply. The transition to this resource may result in reductions in log size and changes in the characteristics of the raw material. The future of the forest industry will depend upon the successful conversion of this resource into forest products. In order to plan new investments and to assess stand management practices, the industry urgently needs information ranging from the effects of silvicultural regimes on volume production and wood value, to the properties and quality of end-products produced from the resource. A program of research into managed second-growth coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) timber values has been undertaken by Forintek Canada Corp. in cooperation with the Pulp and Paper Research Institute of Canada and the Research Branch, B.C. Ministry of Forests.

In conducting such a study, we may usefully draw upon related investigations carried out elsewhere. A decade ago, New Zealand was faced with a similar problem in intensively managed stands of radiata pine. In 1979, the New Zealand Forest Service formed a multi-disciplinary team of forest management and research workers to review management practices, and to develop practical systems to predict the wood quality and the economic and market consequences of various silviculture options. This group, known as the Radiata Pine Task Force, utilized 20 years of research results to build a silviculture stand model (SILMOD). SILMOD simulates the growth of a hectare of radiata pine, and then the harvesting, transporting, and sawmill conversion of that stand. It predicts volume and quality characteristics, which are then used to predict value and yields of timber grades. More recently, a Conversion Planning Project at the Forest Research Institute extended the earlier work of the Radiata Pine Task Force into the areas of processing and marketing. The Conversion Planning Model System links the forest and various processing options to marketing opportunities and requirements for a full range of radiata pine products.

The work of these two groups has been well received in New Zealand and widely recognized as a major step in dealing with decision making under intensive forest management conditions. The shift taking place in Canada to more intensive management with decreasing reliance on old-growth forests creates a situation in which forest managers are faced with the same problem as those in New Zealand. In spite of many decades of silvicultural and utilization research, optimum strategies for management of our future forests are many years away. The New Zealand approach to the development of stand management practices offers much to consider for those of us attempting to deal with similar problems in North America.

In order to consider the objectives of both silviculture and utilization, studies of alternative forest management strategies require data on the relationship between site quality, stocking density, thinning, pruning and fertilization regimes, and product types, quality and values for the softwood species of commercial interest. The New Zealand experience shows how time-consuming and difficult it is to procure such data, particularly for us in Canada where rotation periods for our species are appreciably longer then those proposed for radiata pine. Since solutions are so complex and time consuming, we must develop comprehensive coordinated research programs focussing on the integration of silviculture and utilization. With these objectives in mind, Forintek Canada Corp. established the Douglas-Fir Task Force.

The Douglas-Fir Task Force had the following main objectives:

1. To estimate the physical, mechanical and chemical properties of the intensively managed coastal Douglas-fir resource of the future.
2. To determine the value of this resource for conversion to dimension lumber and pulp.
3. To develop a computer model capable of evaluating the effects of silvicultural treatments in terms of end-product value.

Formation of the Douglas-Fir Task Force

Securing the active support and participation of industry was an absolute necessity in order to ensure the success of the Task Force. Initial contact was made through two committees of the Council of Forest Industries, the Sawmill Operations Committee and the Forest Management Committee. Six of the coastal companies, B.C. Forest Products, Crown Forest Industries (now both under the name Fletcher Challenge), Canadian Forest Products, MacMillan Bloedel, Western Forest Products and C.I.P. Inc. (now called Canadian Pacific Forest Products) all offered to locate suitable stands, fell trees and transport logs to the mill. Canadian Pacific Forest Products made their Ladysmith mill available for the conversion study.

Representatives from each company and the Ladysmith mill manager joined the nine project leaders to form the Douglas-Fir Task Force. The first meeting, March 25, 1985, focussed on site selection, sampling, material requirements, industry cooperation, manpower requirements, and timing.

Site and Tree Selection

It was decided that six stands would be sampled. The age of these stands was to be approximately that of the anticipated rotation age of future managed stands of Douglas-fir, that is, about 50 years. Intensively managed stands of that age do not exist in coastal British Columbia, but 50 year old stands do exist on medium to good sites where stocking densities are not too high and productivity has been at levels that foresters would hope to achieve under intensive forest management conditions. It was this type of stand which was sought for study. In addition, it was decided to obtain as wide a geographic distribution of sites as practical and to represent both the wet and dry regions on the West and East coasts of Vancouver Island as well.

Cooperating companies located 11 suitable stands which were visited by three project leaders and the company representatives early in April 1985. The height, age, diameter and radial growth of randomly selected trees were measured at each site for the purpose of identifying the six best stands. Sites managed by different companies were selected where possible. The locations of the stands are indicated in Figure 1 and the basic stand information listed in Table 1.

The flow of trees, logs, and material selected for each of the study projects is illustrated in Figure 2. The chapter in which the results of each project are reported is indicated. It may be helpful to return to this diagram as one reads through the text in order to keep the link between the study projects in perspective.

It must be kept in mind that the material sampled and therefore the results do not describe the present coastal Douglas fir resource being harvested and marketed today. The results of the basic wood property, pulping, and juvenile-mature wood transition studies do not truly describe the entire stands from which they were obtained since only dominant and codominant trees were selected. It is expected that the trees selected for study represent the range of characteristics which will be produced in future managed stands of this species.

Sampling of the stands for the conversion study was more comprehensive in that the full range of tree diameters was sampled. The sampling plan called for an equal number of trees in each diameter class so that estimates would have equal precision over the full range of stem diameters. However, the results do not properly describe these stands since the sampling was not random. That was not the objective of the study.

This report represents the collective results of the Douglas-Fir Task Force effort. The information provided will help industry plan for the most profitable conversion of our second-growth Douglas-fir resource and will guide forest managers in developing silvicultural plans that will maximize end-product value.

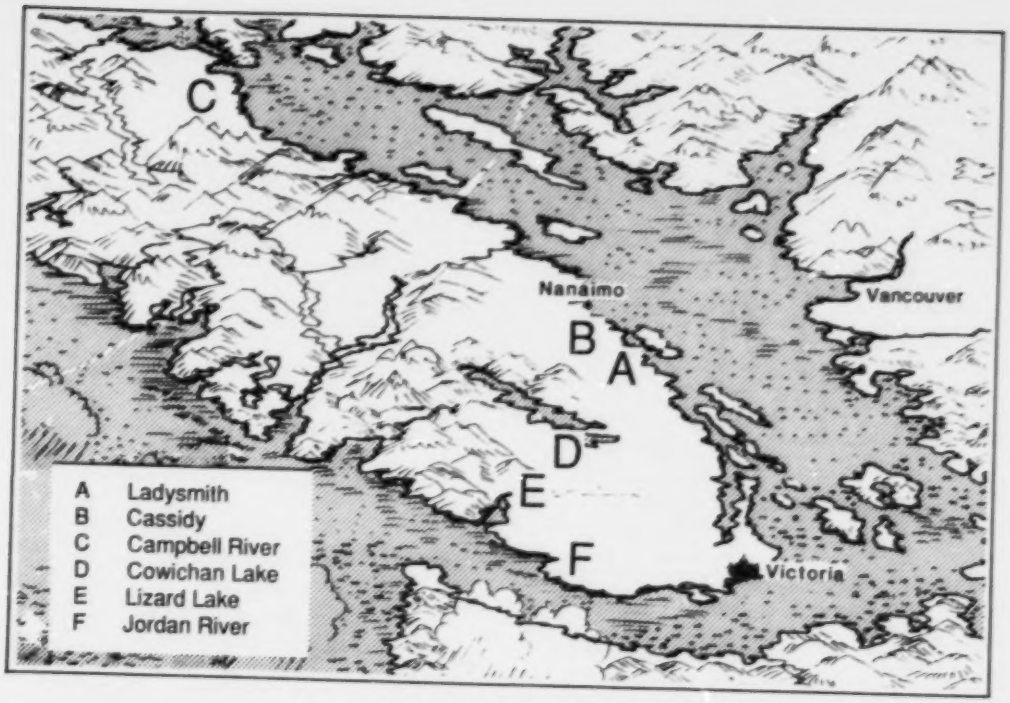


Fig. 1 Location of six study sites on Vancouver Island, British Columbia

Table 1. Selected Stand Characteristics

Location	Cooperating Company	Site Quality	Age (BH)	Avg. Stand Height (m)	DBH			Comments
					mean	s.d.[1] (cm)	range	
Ladysmith	Fletcher Challenge	High Alder/Sword fern	50	38	47.5	11.7	28-70	Wide spacing, some clumping. Considerable self-pruning caused by alder
Cassidy	Macmillan Bloedel	Medium/High Dry/flat Salal/Oregon grape	57	42	47.0	10.7	30-66	Pure Douglas-fir. Good self-pruning. Signs of cutting at Christmas tree age.
Campbell River	Fletcher Challenge	Medium/High Salal/Sword Fern	52	36	43.5	9.2	27-74	Commercial thinning in 1964. Fertilized about 4 years before sampling.
Cowichan Lake	Canadian Pacific Forest Products	High Wet/flat Sword Fern	50	35	56.2	12.8	32-79	Alder/maple site. Open grown. Heavy branches.
Lizard Lake	Fletcher Challenge	High Wet/flat Sword Fern	46	33	51.6	14.0	25-74	Scattered Douglas-fir in hemlock/cedar. Good west coast site.
Jordan River	Western Forest Products	High Wet/slope Sword Fern	60	38	49.4	14.6	25-84	Poor self-pruning despite dense stocking. Douglas-fir widely scattered.

1. Standard deviation

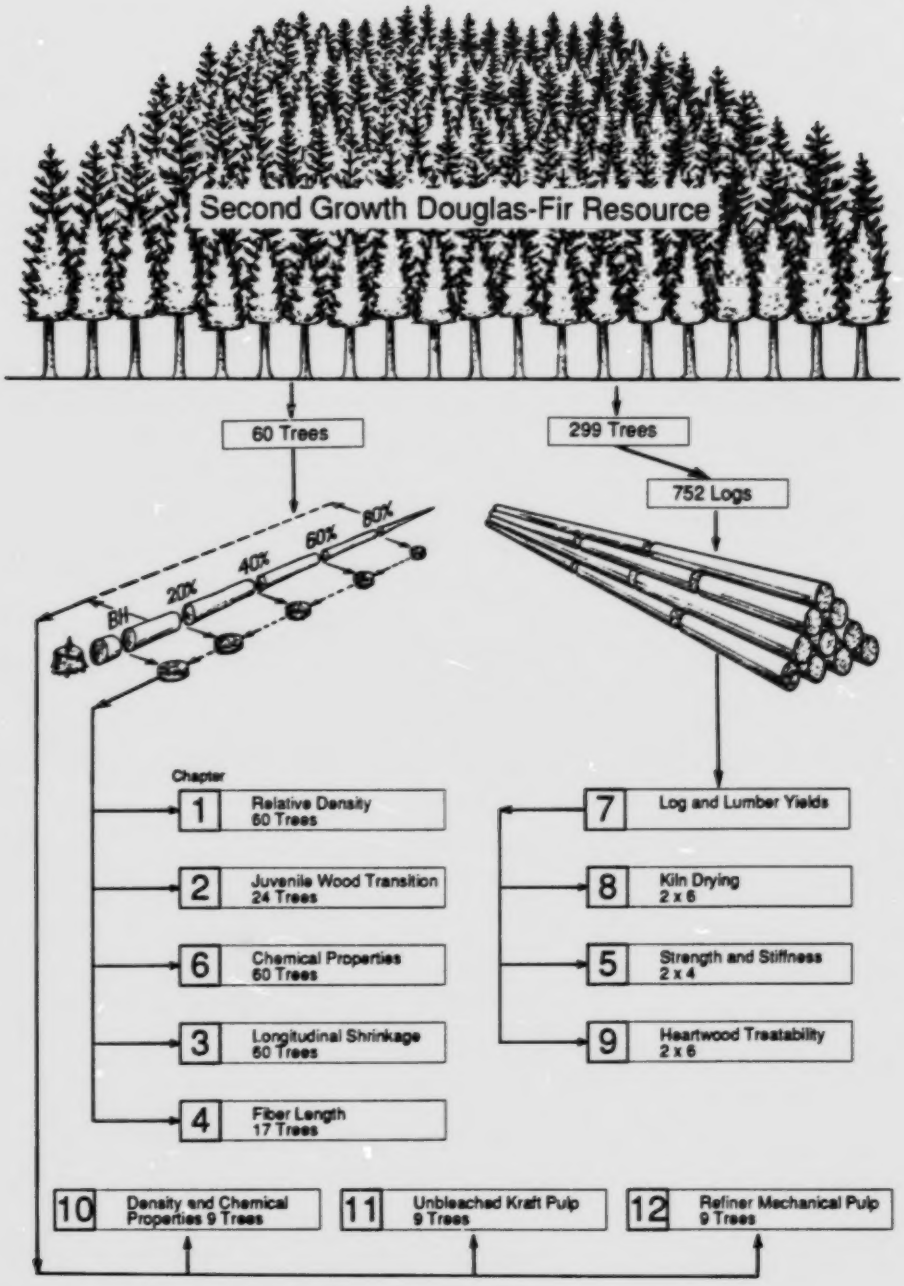


Fig. 2 Source and distribution of trees and material in study projects

PART II : Characterizing the Resource

CHAPTER 1

Relative Density

L.A. Jozsa, J. Richards and S.G. Johnson *Wood Science Department, Forintek Canada Corp.*

Introduction

This report describes the results of x-ray densitometric analysis of approximately 50-year-old Douglas-fir trees from Vancouver Island. Special attention is focussed on the extent and distribution of juvenile wood, and on the influence of cambial age and position in the stem on the relative density of wood.

Wood produced by trees of the same species is often thought to be identical in all structural and physical characteristics. In reality, different pieces of wood even from the same tree are never identical and are similar only within broad limits. Dimensional and physical characteristics (such as ring width, percent latewood width, relative density, etc.) within trees are variable and they exhibit a range of values. The variations can be related to the radial (pith-to-bark) and axial (base to top of stem) position of the sample within the tree.

The dimensional and physical variables in wood are influenced by the following factors:

1. Cambial age;
2. Genetic controls that govern the form and growth of the tree; and
3. Environmental influences, such as climate, geology and nutrient supply.

Because of the interactions of these influences, it is difficult to ascribe variability in tree rings to a single factor or even to a combination of factors affecting tree growth (Panshin and de Zeeuw, 1980).

Wood quality is linked to end-use requirements, which are stipulated through grades, specifications, and code regulations (Johnson, 1986). Density is generally considered to be the single most important indicator of clear wood quality. It is the primary determinant of clear wood strength and yield of pulp per unit wood volume. It is also related to heat per unit volume produced during combustion, to shrinkage and swelling, to heat transmission, to machining, and to other properties. Unfortunately, density is difficult to measure on a small scale (like individual annual rings) by conventional methods.

Principles of Tree Growth and Wood Anatomy

Because wood quality will be discussed here in terms of density, it would be helpful to review some of the basic concepts and definitions of tree growth and wood anatomy, that is, the conditions that determine density.

Although the crown of a tree is both the source of nutrients and the regulating center for wood production, wood is not produced directly by photosynthesis. Rather, wood results from successive divisions of the vascular cambium, using energy derived from the products of photosynthesis. After cambial division each successive cell undergoes enlargement, wall thickening, and lignification. The rate of cell division and final size are both thought to be largely influenced by growth regulating hormones (Megraw, 1985).

The growing tree forms large diameter, thin-walled fibers in the early part of the growing season (earlywood), and smaller diameter thick-walled fibers during the latter part (latewood). Collectively, these fibers form an annual ring. Radial growth begins first near the top of the tree and proceeds gradually downward in the stem, resulting in more earlywood and wider rings near the pith in the upper crown region. Transition to latewood occurs first near the base, farthest from the source of auxin supply, and proceeds upwards. Therefore, the density of an individual fiber is determined by its relative position, that is, its distance from the active live crown region, and by the time of its formation (Larson, 1969; Megraw, 1985).

The relative density of most commercially important Canadian softwoods ranges from about 0.2 in the earlywood to about 1.0 in the latewood. The average relative density of the different softwood species ranges from about 0.3 for western red cedar to 0.55 for Douglas-fir and western larch, largely dictated by the proportion of the low density earlywood and high density latewood in the annual rings.

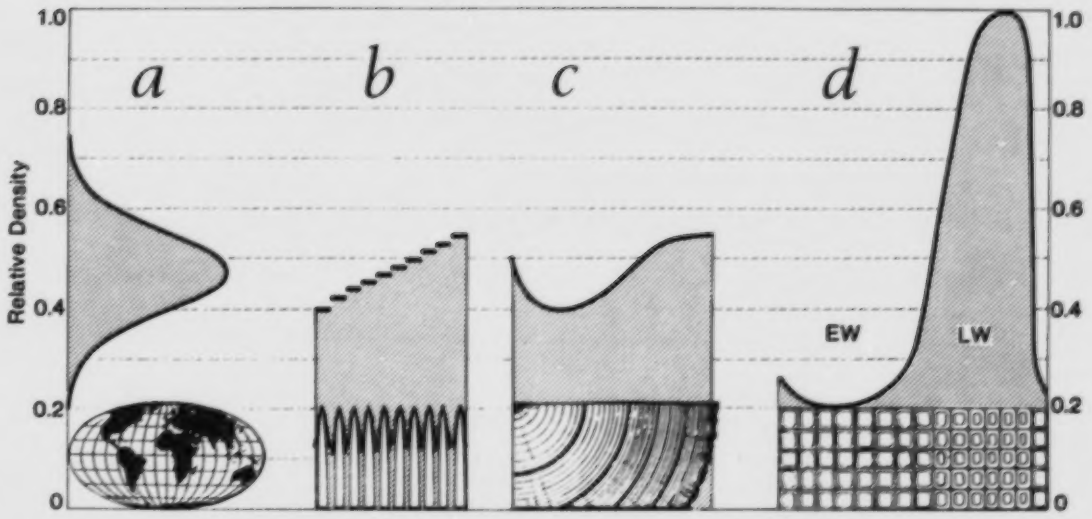


Fig. 1-1 Relative density variation in Douglas-fir:
(a) between trees, global variation,
(b) between trees, differences in a stand,
(c) within tree, trend from pith to bark,
(d) within annual ring, earlywood/latewood

Sources of Relative Density Variation

The relative density of Douglas-fir wood can be discussed from a variety of perspectives, starting with species average and range, tree-to-tree differences in the stand, within tree trends from pith-to-bark and from base to the top of the stem, and within annual ring variability. Figure 1-1 illustrates this variety, ranging from the macroscopic to the microscopic perspective.

For example, the "global perspective" of relative density distribution is shown for Douglas-fir in Figure 1-1a. This bell-curve approximation includes all Douglas-fir trees from British Columbia (coastal and interior), Washington, Oregon, California, Europe, New Zealand, and elsewhere. One would expect a normal distribution with the mean between 0.45 and 0.50, flanked by the extreme lows and highs in the 0.3s and 0.6s respectively.

The expected tree-to-tree relative density differences in the stand are illustrated in Figure 1-1b. If one were to sample ten dominant and codominant trees in a stand and determine the average stemwood relative density, one would expect a certain difference between the least and the most dense trees. In this example (Figure 1-1b) the stemwood relative densities range from 0.40 to 0.55. Of course, a greater number of trees would most likely provide a wider range. These tree-to-tree differences in the stand are thought to be mainly genetic in origin (Kennedy, 1970; Megraw, 1985 and 1986, Bastien *et al.*, 1985).

The biological tree-age component is shown in Figure 1-1c. In previous exploratory work (Jozsa and Kellogg, 1986) average yearly ring density trends were examined from pith-to-bark at several sampling heights in Douglas-fir. The results indicated relatively low density juvenile wood in Douglas-fir for the first 15-20 years of growth. Then a rapid increase was evident to about age 30, followed by a stable or slightly increasing density trend. Similar trends were observed by other workers in Douglas-fir and in some pine species as well (Megraw, 1985; Pearson and Ross, 1984; Kennedy and Warren, 1970; Richardson, 1961; Bendtsen and Senft, 1986). This pith-to-bark density trend was used to establish the juvenile wood and mature wood transition for Douglas-fir. It was noted that the transition was not abrupt, or step-like, but rather gradual.

Within annual ring density variation is illustrated in Figure 1-1d. Interestingly, the greatest density difference was observed in Douglas-fir on the microscopic level within the annual ring. Between low density earlywood and high density latewood the differences are about four-fold, from about 0.25 to 1.00. These differences were attributed in the above discussion to growth-regulating hormones. However, earlywood and latewood production in a tree is seasonally driven (Kennedy, 1970).

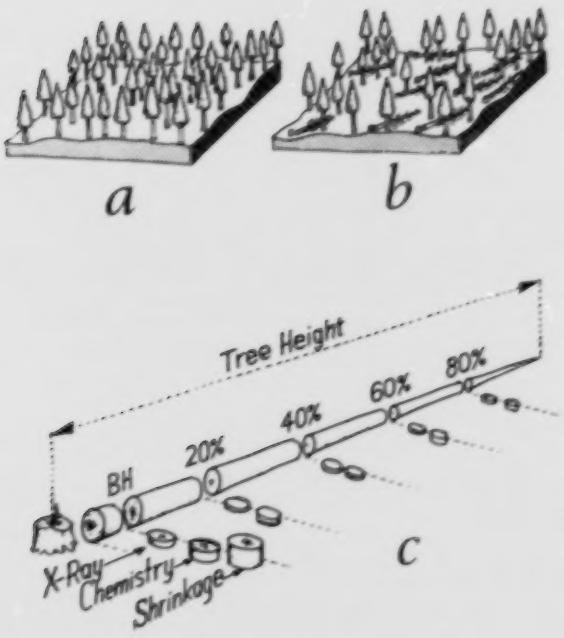


Fig. 1-2 Stand and tree sampling plan

Materials and Methods

Site Selection and Sampling

The location of the stands (Figure 1) and the basic stand information (Table 1) were described in the introductory section. That information was obtained during the exploratory visit to each site. At each location diameter measurements were based on 25 trees selected at random.

From each of the six stands (Figure 1-2a), ten dominant or codominant trees were selected and felled (Figure 1-2b) for the study of basic wood properties. Cross-sectional disks were cut from each tree at five height positions. These were at breast height (BH = 1.3 meters above ground) and at one-fifth intervals of total tree heights (Figure 1-2c). At each of these positions two disks were cut, one 2.5 centimeters thick, for densitometric analysis, and the second, 5.0 centimeters thick for fiber length measurement (Chapter 4) and chemical analysis (Chapter 6). Disk samples were cut, as far as possible, from the center point of every internode at the appropriate height level. This strategy was adopted on the strength of previously published results of greater anatomical variability near the nodes (Richardson, 1961). In addition, a 35 centimeter thick disk was collected just above the BH position (Figure 1-2c) as a source of material for longitudinal shrinkage measurements (Chapter 3). Furthermore, wood density measurements were made on increment cores at BH for the 10 trees at each site for selecting one average, one high and one low density tree for pulping studies (Chapter 10). From each of these three sample trees a two meter long bolt was cut above BH and a three meter long bolt was collected in the crown-wood, below the 80 percent sampling height for both unbleached kraft (Chapter 11) and refiner mechanical (Chapter 12) pulping evaluation.

Sample Preparation and X-ray Densitometry

Two average radial subsamples were cut from each densitometric cross-sectional disk. These pith-to-bark radial strips were about 5 millimeters wide and 5 millimeters thick. After air-drying they were cut to a uniform thickness of 1.96 millimeters on a twin-blade saw. The surfaced samples were extracted in a soxhlet apparatus in alcohol-benzene (1:2 by volume) solution for three days, and in hot water for two days. The extractive free radial strips were then air-dried to about eight percent equilibrium moisture content. The air-dried strips were placed on X-ray film with density-calibration wedges and exposed at the appropriate grain angle to x-radiation. The film was then developed to produce an X-ray negative contact-image of the tree-ring sample. Calendar year dates and other information were marked on each radiograph. Radiographs were scanned on a computerized light-transmission densitometer to generate ring width (resolution 0.01 millimeters) and ring density data. Tree-ring data were stored on magnetic tape for further processing. More detailed descriptions of these densitometry techniques have been published by Parker *et al.* (1980), Jozsa and Myronuk (1986), and Jozsa *et al.* (1987).

Tree-Ring Data

Relative density values were expressed on an oven-dry volume and weight basis. The quoted numbers are, therefore, about 10 percent higher at the 0.45 level than the conventional basic wood density, which is expressed on a green volume and oven-dry weight basis.

The Tree Ring Input Program (TRIP) was used for data acquisition to obtain the following eight tree-ring variables for each annual ring: ring width, earlywood width, latewood width, ring density, earlywood density, latewood density, minimum ring density, and maximum ring density.

In addition to these variables, TRIP recorded 100 intra-ring density profile values for each annual ring, regardless of its width. This was designed to simplify the format of these values for storage and permit the summing and plotting of intra-ring density profiles. The percent latewood width values were based on density levels and not on Mork's classical definition (Mork, 1928). Specifically, the following relative density boundaries were assigned for earlywood and latewood in Douglas-fir: from the beginning of the ring until the relative density increases to 0.54, wood is classified as earlywood; from that point (0.54) until the relative density falls again to 0.45, wood is classified as latewood (Heger *et al.*, 1974; Jozsa *et al.*, 1987).

Tree Age and Juvenile Wood Determination

In the various tables and figures of the results and discussion, average tree ages will be given at BH. At BH the trees range in age from a low of 33 to a high of 71. At times the numerical average will be quoted for the sixty trees, the average of 10 trees at each of the six sites, and at the age of the youngest sample tree at each site. The latter of these will be used when summaries are made on a full balanced set of 10 or 60 trees. The reason for this is that the means can shift abruptly when the younger trees start dropping out in the summarizing process.

In this study, we defined juvenile wood as the first 20 years of growth, adjacent to the pith, at each height level. The juvenile-mature wood boundary was established by examining relative density changes from pith-to-bark, and by selecting a transitionary zone between the relatively low to high density wood. The density trends were examined at all five height levels and the first 20 year period of growth was selected as the juvenile phase of tree growth. Therefore, the central juvenile wood cylinder which encompasses the pith extends from the base of the tree to the top.

Assessment of Entire Stemwood Density Trends and Presentation of Data

Reconstructing past growth and development of a tree by measuring annual rings from pith-to-bark at a number of points along the bole, that is, a complete stem analysis, has many applications in forestry. Forintek's stem analysis technique is particularly informative because, in addition to ring width, it includes wood density measurements.

Ring density was classified along three different gradients as described by Duff and Nolan (1953), and Fritts (1976). The first classification, gradient (1), represents the horizontally arranged sequence of rings which is affected by climatic variation and other changes in growing conditions along with the increase in tree age. Yearly average densities for whole ring, earlywood and latewood were summarized for the ten intensively sampled trees (for each of six sites) and these data were plotted for all five sampling heights. The second classification scheme (2) represents the diagonal series of rings at various stem heights for the same calendar year and expresses changes associated with increasing stem height and decreasing cambial age. The third classification scheme (3) represents a vertically arranged sequence, with each ring sampled at a given cambial age, i.e., the summaries are made by age from the pith.

Average stem profiles were drawn to scale, representing tree height, stem diameter and taper. Density contour lines were drawn with the aid of pith-to-bark yearly average density plots as a function of cumulative ring width for each sampling height. This approach was taken to quantify density distribution in the stem. Specifically, what portions of the stem contain relatively low and high density wood.

Three arbitrary relative density zones were delineated and mapped in the stem:

1. average range for the species (0.46-0.49 for Douglas-fir);
2. below average (<0.46); and
3. above average (>0.49)

The above three density zones were superimposed on profiles depicting pith-to-bark trends at the various sampling points along the bole.

Total stemwood density trends were calculated and plotted by increasing age (at BH) and by total stemwood volume (cubic meters). Therefore it is possible for the forest manager, silviculturalist, or research worker to look back in time and describe a particular tree at any earlier age. For example, it is possible to ask questions such as, "Are the high volume producers the low-density trees?" or "At what earliest age can one rank trees in a progeny test by wood density, with confidence that the rankings will remain the same at harvest age?"

Growth Rate versus Relative Density Comparison

In some tree species there is a strong correlation between growth rate and relative density, usually a negative one. In other words, wide annual rings contain low density wood (Olesen, 1976; Taylor *et al.*, 1982). Megraw (1985, 1986) compared many Douglas-fir trees of identical age but of varying diameters and found no significant correlation between disk diameter and disk relative density. The key word in such comparisons is cambial age. In this study, comparisons were made by graphing entire stemwood densities with tree diameters at BH. In addition, average ring densities were compared with ring width at identical cambial age.

Relative Density Comparisons of Second-Growth with Old-Growth Douglas-Fir

Unfortunately, very little information exists on relative density distribution in old-growth Douglas-fir by yearly pith-to-bark and base-to-top stem analysis. However, at various times the Canadian forest products sector has documented the relative density of the Douglas-fir resource being harvested and the various dimensional lumber products being manufactured. Such relative density baseline information was utilized in our comparison with our study trees. McGowan (1968) and Cook (1988) published relative density information for dimensional lumber, and Jessome (1977) reported tree averages and standard deviations.

Biomass Productivity in the Stemwood

The yearly ring density and ring width data were integrated by a stem analysis approach to determine the change in the average relative density of the entire stemwood as a function

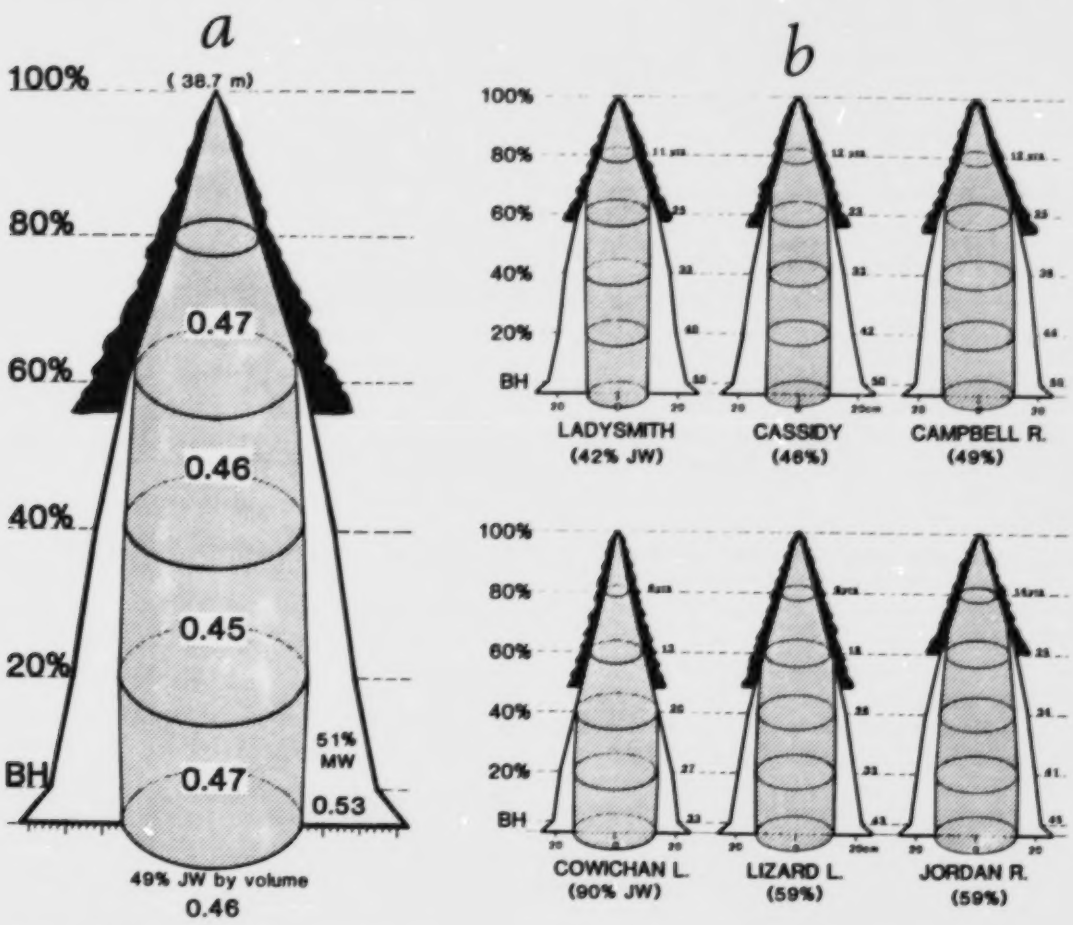


Fig. 1-3 Radial and axial distribution of juvenile wood in 33 to 71 year old Douglas-fir:
(a) average juvenile wood cylinder of 60 trees at age 50,
(b) the extent of juvenile wood at six sites

of increasing age and total stem volume. Finally, combining the growth layer volumes with their respective relative densities, the yearly growth layer weights in the stemwood were determined from pith-to-bark, from the first growth layer at BH to the last annual ring beneath the bark. Site productivity curves were established both by tree age (pith being the common reference point, curves "left justified") and by calendar years (the last annual ring beneath the bark being the common reference point, curves "right justified"). Both comparisons are equally valid. The first type, by tree age, gives the site productivity, while the second, by calendar date, often reveals climate related signals.

Results and Discussion

The Average Tree and Its Juvenile Wood Core

The average second-growth Douglas-fir tree chosen for this study was 50 years old (range 33-71 years), 38.7 meters tall, capped with a 17.1 meter long live crown. Its diameter was 55 centimeters (38-75) at BH, outside bark, and 46.4 centimeters inside bark. This average tree had a volume of 2.45 cubic meters at age 50 and an average stemwood relative density of 0.48. Consequently, the stem weighed about 1175 kilograms (oven-dry basis). Through detailed stem analysis it was established that by volume 49 percent (1.2 cubic meters) of the stem was juvenile wood (Figure 1-3), the relative density of which was 0.46. At BH the moisture content of the juvenile wood (inner heartwood) was 37 percent, at 80 percent height level (all sapwood) it was 118 percent.

Radial and axial distribution of juvenile and mature wood is shown for the average Douglas-fir tree at age 50 in Figure 1-3a. Although the stem diameter was drawn with an exaggerated horizontal scale, the stem taper is drawn to scale. The average growth rates at the various sampling heights were quite similar, resulting in a nearly cylindrical shape of the inner juvenile wood in the axial direction.

Table 1-1. Summary of Tree and Stand Characteristics Based on Ten Sample Trees Collected for Basic Wood Property Study

	Site Name	Age at BH (yrs)	Range (yrs)	DBH (cm)	Stump Diameter (cm)	Height (m)	Crown Length (m)	Stocking Density (stems/ha)	Basal Area (m^2/ha)	Percent Douglas-Fir in Stand
A	Ladysmith	55	50 - 71	56.9	61.5	42.2	17.3	----	----	----
B	Cassidy	58	50 - 71	54.5	59.5	41.7	17.7	654	46	100
C	Campbell River	53	50 - 55	53.6	64.4	38.8	17.5	395	43	100
D	Cowichan Lake	38	33 - 46	53.1	63.4	33.6	17.1	381	42	43
E	Lizard Lake	46	43 - 52	55.3	65.2	35.8	18.1	705	51	34
F	Jordan River	53	45 - 55	56.7	63.8	40.3	15.9	523	52	40
	Average of Six Sites (60 trees)	50	45 - 58	55.0	63.0	38.7	17.1	530	47	63

The extent of the inner juvenile wood is shown at the six sampling sites in Figure 1-3b. Tree heights were standardized to facilitate comparisons between sites, sampling heights, tree ages, base of live crowns and stem tapers. Stemwood diameter, stem taper and live crown length were drawn to scale, on the basis of measurements taken during sample collection in the field and measurements by x-ray densitometry. The three sites (Ladysmith, Cassidy, and Campbell River) at the top of the figure represent sites on the east coast of Vancouver Island, and the bottom three (Cowichan Lake, Lizard Lake, and Jordan River) represent the sites on the west coast. Site average of 49 percent juvenile wood content (by volume) ranged from 42 percent at Ladysmith, to 90 percent at Cowichan Lake. As can be seen, these differences are age related: the average on the Ladysmith site had 42 percent juvenile wood at BH age of 50 years. In contrast, the Cowichan Lake trees were only 33 years old. Thus, mature wood growth lasted only 13 years at BH (age at BH minus 20 years), 7 years at the 20 percent height, and there was no mature wood at the 40 percent sampling height. Therefore, the Cowichan Lake trees at age 33 consisted entirely of juvenile wood in the top 60 percent of their stems. At the other five sites this transition to juvenility occurred at about 65 percent height level, resulting in entire juvenility only in the top 35 percent of tree stems.

Site average diameters at BH were quite similar, ranging from 53.1 centimeters at Cowichan Lake to 56.9 at Ladysmith (Table 1-1). The Cowichan Lake trees were very vigorous growers. At the average BH age of 38 their tree height was 33.6 meters, with a 17.1 meter crown length. The combination of youth and vigor in these trees resulted in a relatively conical stem taper and a long live crown (Figure 1-3b). Comparatively long crowns also occurred at the Lizard Lake site. In most respects the other site averages are quite comparable to the overall means for the 60 trees.

The average relative density of the central juvenile wood cylinder was 0.46. The density distribution from the base to the top was quite uniform: 0.47, 0.45, 0.46, and 0.47, corresponding to cylinders 1, 2, 3 and 4 (Figure 1-3b). These results confirm earlier findings by Jozsa and Kellogg (1986). Although considerable tree-to-tree variation was observed, in terms of site-to-site comparisons, juvenile wood properties in these 60 Douglas-fir trees were quite uniform in relative density and rate of growth.

Average Ring Density Trends From Pith-To-Bark

Average ring density trends were examined from pith-to-bark at the five sampling heights as a function of cambial age and radial distance from the pith. At BH the general trend in yearly average ring density, including all 60 sample trees, is a declining one from the pith to about age seven from about 0.52 to 0.44 (Figure 1-4a). Since the average relative density of the BH disk is about 0.53, this decline is about 15 percent. A rapid increase in ring density is evident from age 10 to 30, from 0.46 to 0.56, or about a 19 percent increase again based on the disk average ring density at BH, 0.53. From age 30 to 50 average ring density levels off and increases only slightly, about four percent, from 0.56 to 0.58.

At the 20 percent sampling height a similar density pattern was observed as at BH: initial decline, rapid increase, followed by a gradual increase. The only major difference was that at the 20 percent height level relative ring density was consistently lower, by about 8 percent, from pith to bark. The average disk density at this sampling height was 0.49, with 38 annual rings at BH age of 45 years. Pith-to-bark average ring width was about 5 millimeters.

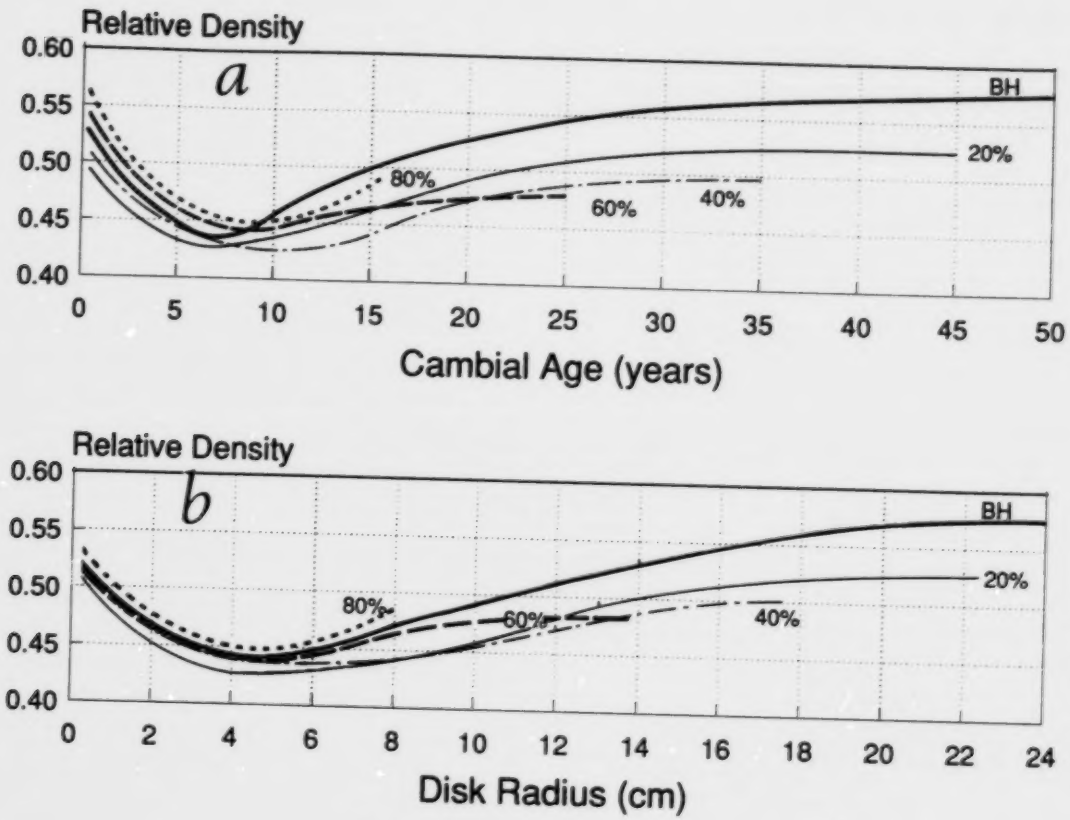


Fig. 1-4 Average ring density versus:
(a) rings from pith, or
(b) disk radius by sampling height

At the 40 percent and 60 percent sampling positions the average disk density was 0.46, with 30 and 22 annual increments, respectively. Average ring width was about 5 millimeters at both sampling heights. Ring density decreased from year one to the tenth annual ring in both disks: from 0.50 to 0.43 at the 40 percent height level, and from 0.54 to 0.45 at the 60 percent location. A more gradual increase, compared to BH and 20 percent height levels, followed the declining trends to about 0.50 and 0.48 relative density at the 40 and 60 percent heights. Although the 80 percent height disk sample contained only 11 annual rings, its density trend was very similar to the innermost rings at BH (Figure 1-4a). It appears that with the exception of the 80 percent sampling height, none of the other height levels ever reach the BH density values.

Figure 1-4b shows average ring density trends by radial distance from the pith. This graphic presentation of ring density and radial dimensions was used as an aid in mapping the distribution of juvenile and mature wood in the stem (Figure 1-3). Above average ring density (>0.49), below average (<0.46), and average (0.46-0.49) ring density zones in the stemwood were also delineated with the help of Figure 1-4b.

Total Stemwood Density Trends

Total stemwood density trends were plotted by increasing age at BH and total stemwood volume, and are shown in Figure 1-5. Three notable features can be observed: first, the range, or the difference between the low and high density sample trees; second, the rate of change in density from inner juvenile phase to outer wood maturity; and third, the ranking of the trees.

Figure 1-5a illustrates 10 sample trees from the Lizard Lake site, showing about 0.15 density units difference between the least and most dense trees. This difference at the site average age of 43 represents a 32 percent range in total stemwood density, the site average being 0.48. In fact, the range, from 0.40 to 0.55 relative density, includes all 60 trees in the study. Therefore the Lizard Lake trees show a very heterogeneous

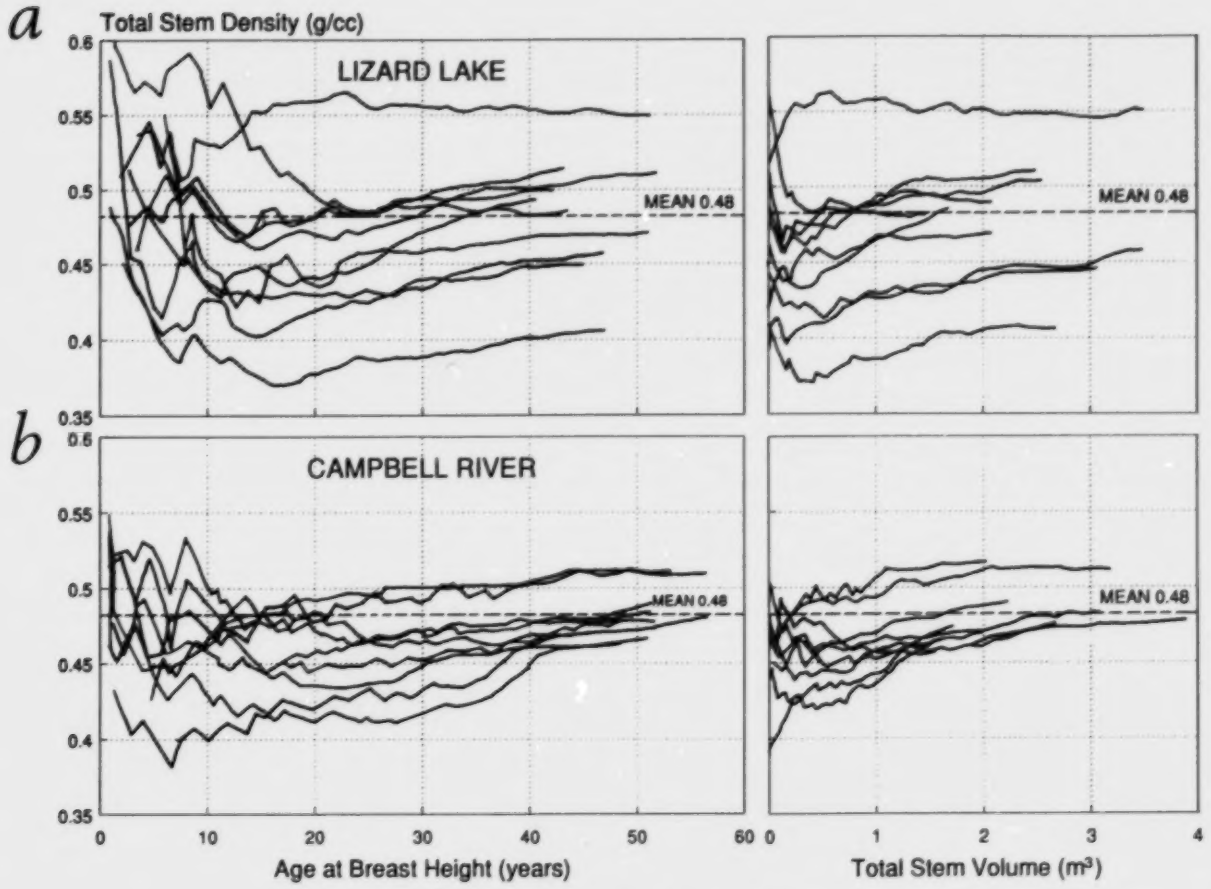


Fig. 1-5 Total stemwood density for individual trees versus age at breast-height and stem volume at:
(a) Lizard Lake, a heterogenous site, and
(b) Campbell River, a homogenous site

density distribution. By contrast, the 10 Campbell River sample trees are quite homogeneous. At age 50 the density range is only about 10 percent (Figure 1-5b), although the site average for stemwood density is 0.48. Total stemwood density trend plots as a function of total stemwood volume show the range of tree volumes for the 10 trees for the two sites. At Lizard Lake the average stem volume was 2.22 cubic meters and at Campbell River 2.3 cubic meters; individual tree volumes at the two sites, respectively, ranged from 1.5 to 3.5, and from 1.9 to 3.9 cubic meters. Table 1-1a lists site average stemwood and juvenile wood volumes, densities, and other related information.

From the utilization point of view tree-to-tree variation in average stemwood density is important, even with identical site averages, because it is the lower fifth percentile of strength, and indirectly density, which determine the allowable working stresses for dimension lumber. Therefore, in theory, the site with a homogeneous density distribution will rate higher in strength than the heterogenous site, all other variables being equal.

Relative Density Distribution in the Stemwood

Table 1-2 lists average disk density, diameter, and the number of annual increments for the five sampling heights for the six sites. This information is shown in Figure 1-6 with relative density distribution of low, average and high density wood in the average stem from the base-to-top and from pith-to-bark. Stem diameter and number of annual rings at the different sampling heights are shown in Figure 1-6a. Note that the rate of growth is quite uniform at the five sampling heights: about 1 centimeter diameter increment per year (average ring width about 5 millimeters).

Average disk density values are shown in Figure 1-6b for the five height levels. It can be seen that average disk relative density declines from BH through 20 percent to the 40 percent height level, from 0.53 to 0.46. At the 60 and 80 percent

Table 1-1a. Summary of Average Stem Wood and Juvenile Wood Volume, Relative Density, and Other Related Information at the Age of the Youngest Tree at Each Site

Site Name	Age at BH (years)	Stem Volume (m^3)	Average Stem Relative Density	Stem Density Range (min - max) (%)	Juvenile Wood Cylinder Volume (m^3)	Percent Juvenile of Total Volume (%)	Juvenile Wood Relative Density
A Ladysmith	50	2.78	0.47	19	1.18	42	0.43
B Cassidy	50	2.26	0.51	13	1.03	46	0.48
C Campbell River	50	2.30	0.48	10	1.12	49	0.46
D Cowichan Lake	33	1.36	0.48	17	1.22	90	0.47
E Lizard Lake	43	2.22	0.48	32	1.31	59	0.47
F Jordan River	45	2.30	0.48	19	1.35	59	0.45
Average of Six Sites (60 trees)	45	2.20	0.48	18	1.20	55	0.46

Table 1-2. Average Disk Density (g/cm^3), Diameter (cm) and the Number of Annual Increments (yrs) at the Five Sampling Heights for the Six Sites (at the the BH age of the Youngest Sample Tree at Each Site)

Sampling Height Overall Disk Average	A Ladysmith	B Cassidy	C Campbell River	D Cowichan Lake	E Lizard Lake	F Jordan River	Average of 60 Trees
80% Relative Density	.46	.48	.46	.49	.45	.48	.47
Diameter	12	11	12	8	11	13	11
Number of Rings	11	12	12	6	9	14	11
60% Relative Density	.45	.49	.46	.49	.45	.47	.46
Diameter	26	23	26	18	23	25	24
Number of Rings	25	23	25	13	18	25	22
40% Relative Density	.44	.49	.46	.46	.47	.46	.46
Diameter	34	31	34	28	33	34	32
Number of Rings	33	33	36	20	26	34	30
20% Relative Density	.46	.52	.49	.49	.48	.48	.49
Diameter	39	36	38	36	38	39	38
Number of Rings	40	42	44	27	33	41	38
BH Relative Density	.52	.56	.54	.50	.52	.54	.53
Diameter	46	43	42	41	44	45	44
Number of Rings	50	50	50	33	43	45	45
Weighted Average Relative Density of Whole Stem	.47	.51	.48	.48	.48	.48	.48

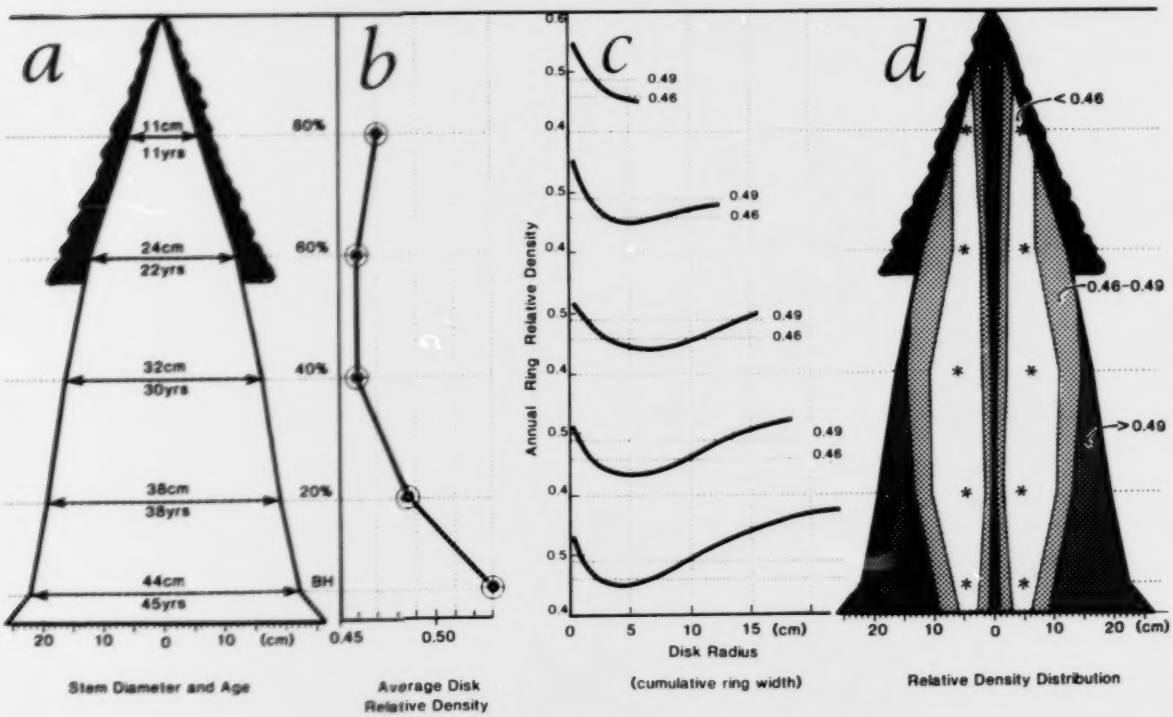


Fig. 1-6 Diameter, taper and density distribution for the overall average stem at age 45:
(a) Disk diameter and number of annual rings at the five sampling heights,
(b) average disk densities,
(c) pith-to-bark relative density profiles,
(d) relative density distribution in the stem

height the average disk relative densities were, respectively, 0.46 and 0.47. On average, the BH disks are about 10 percent more dense than the 20 percent disks. It is also evident from Table 1-2 that the 20 percent height level disk is a much better estimator of whole stem density than the BH position for trees this age. At each of the six sites the 20 percent disk density is within 0.01 density unit of the average stem density. The numerical averages for the 60 trees' average stem density and 20 percent disks are 0.48 and 0.49, respectively. Therefore, if whole stem density estimates are required for this type of trees at about age 50 the 20 percent height level disks could be utilized.

For reference, Figure 1-6c illustrates the same pith-to-bark average ring density trends at the five sampling heights as was shown in Figure 1-4. However, there is one notable difference. In Figure 1-6c ring density trend lines are offset to correspond to their respective height positions.

With the help of Figure 1-4b, the relative distribution of low, average, and high density wood in the stem was mapped from the base to the top and from pith-to-bark (Figure 1-6d). The mature wood with a density greater than 0.49 envelops the stem and extends from the butt to near the base of the live crown. This evidence supports Larson's (1969) biological hypothesis as well as the observations of Megraw (1985) and Di Lucca (Chapter 2) that mature wood is produced below the active live crown. Furthermore, the low density juvenile wood, grown under the influence of the live crown, extends through the entire stem from the base to the top. This finding may have practical implications for resource allocation and pruning prescriptions.

This form of density mapping (Figure 1-6d) may make the wrong impression because density changes from low-medium-high zones are not stepped. Density changes and shifts from one zone to another are very gradual, as shown in Figure 1-6c. For example, the minimum density values at the five sampling heights are reached about 4 to 6 centimeters from the pith, at about the mid point in the <0.46 relative density zone. An asterisk (*) marks the position of minimum pith-to-bark ring density at the five sampling heights in Figure 1-6d. These points were at the sixth to tenth annual increment (Figure 1-4a) at the different height levels. Average tree profiles with density zones are shown in Figure 1-7 for the six Vancouver Island sites.

Intra-Ring Density Profiles

The intra-ring density profiles of juvenile and mature wood are presented in Figure 1-8. Also shown in this figure is a

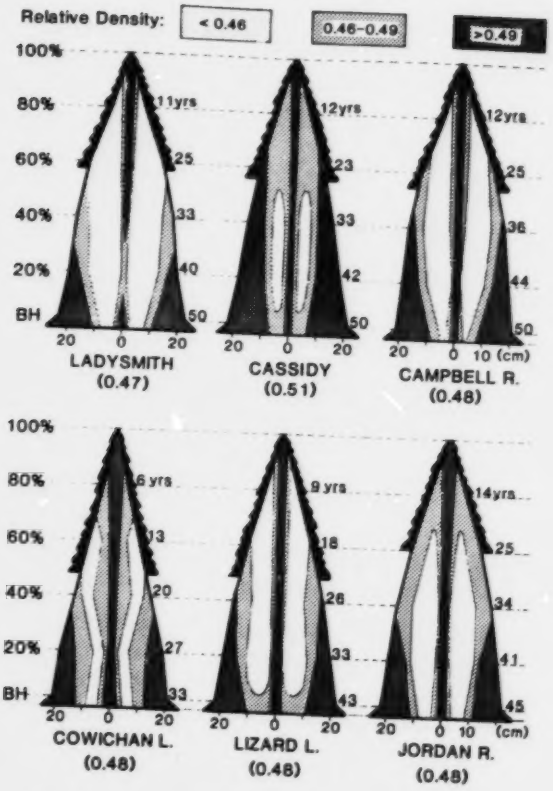


Fig. 1-7 Average tree stem profiles and relative density distributions for the six study sites

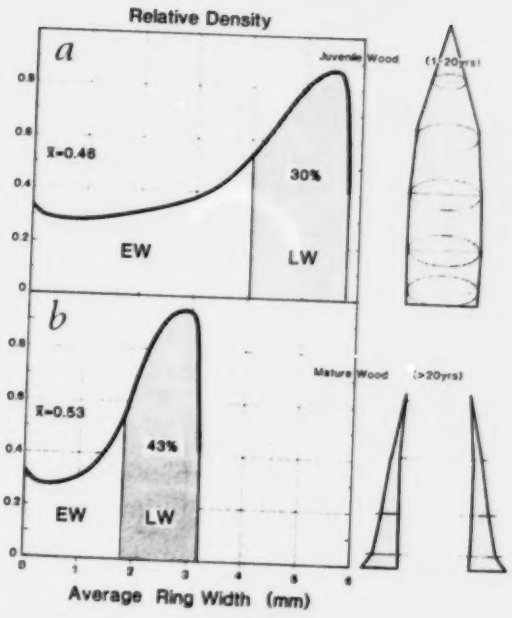


Fig. 1-8 Average intra-ring density profiles for all 60 study trees:
(a) average of all annual rings in the juvenile wood,
(b) average of all rings in the mature wood

sketch of the juvenile wood cylinder (with its conical top above the 80 percent height level) and outer mature wood.

Figure 1-8a shows the average density profile of about 5500 annual rings from the juvenile cylinder of 60 trees, from five sampling heights. The average annual ring density profile of the mature wood is a composite of about 3300 annual rings (Figure 1-8b). At each sampling height the juvenile wood annual rings tended to be relatively wide, about 5.8 millimeters on the average, ranging from 4.4 to 7.1 millimeters for the six sampling sites (Figure 1-9). Average ring density was about 0.46, ranging from 0.29 for the low density earlywood to 0.88 for the maximum density latewood. By width, about 30 percent of the annual ring was latewood (Figure 1-8a). In contrast, 43 percent of the mature wood annual ring was latewood (Figure 1-8b).

Mature wood, consisting of the wood from the 21st ring to bark at each sampling height, was relatively fast-grown as well with an average ring width of 3.2 millimeters. On the average, ring width ranged from 2.9 to 4.9 millimeters at the five sampling heights at the six sampling locations (Figure 1-9). The relative density of the average annual ring in the mature wood zone was 0.53, ranging from 0.28 for the low density earlywood to 0.95 for the maximum density latewood.

In summary, juvenile wood had greater density homogeneity than mature wood. This may have an impact on machinability. For example, it is the density uniformity, resulting from the small amount of latewood, that makes white pine, yellow cypress, and western red cedar such excellent carving stock (Echols, 1972). Density distribution and mean density provide a measure of wood uniformity and suggest its degree of suitability for end uses.

These density differences between the earlywood and latewood components of the annual ring are far greater than the tree-to-tree, base-to-top, and cambial age related pith-to-bark density differences in these 50 year old Douglas-fir trees. At the same time, it is also noteworthy that the greatest contributor to relative density is the proportion of latewood in the annual ring, not minimum and maximum density.

Growth Rate - Relative Density Relationships

As a first test, to investigate the relationship between growth rate and relative density, BH tree diameters were compared

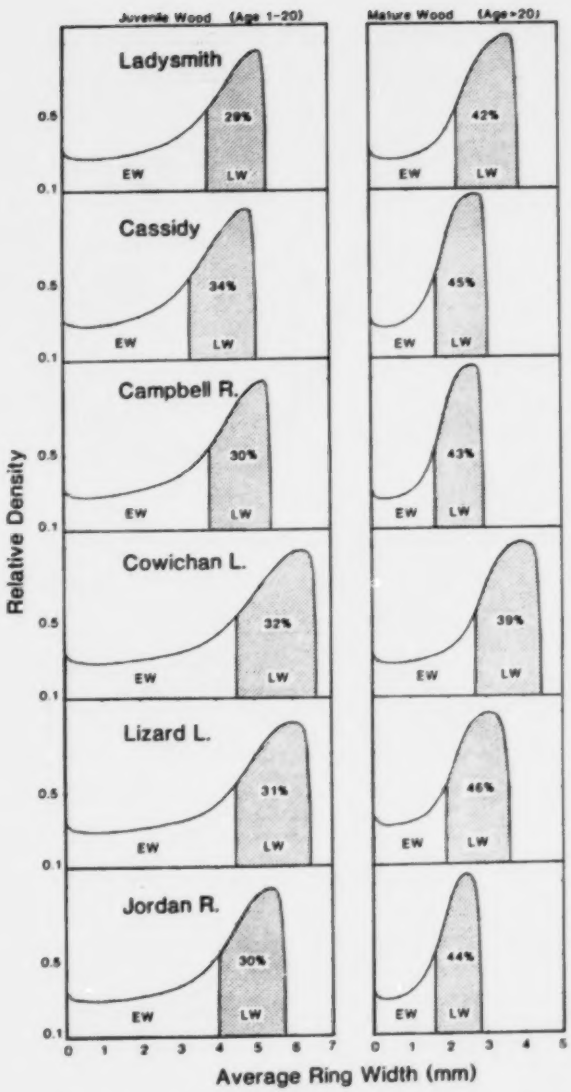


Fig. 1-9 Intra-ring density profiles of juvenile and mature wood for the six study sites

with total stem densities. The results of this comparison for the 60 trees are shown in Figure 1-10. No obvious relationship is evident in this scattergram plot. In other words, small diameter trees were not more dense than the large diameter ones. While tree diameters ranged from 36 to 75 centimeters, and stemwood relative density ranged from 0.40 to 0.55, there is no consistent relationship between these two variables.

On a smaller scale, individual annual ring widths were compared with their respective average ring densities. In Figure 1-11 the 5th, 20th, and 40th annual rings were selected at BH from the 60 sample trees for this comparison. These annual rings represent the inner juvenile wood (the 5th annual ring from the pith, Figure 1-11a), transitional wood (20th

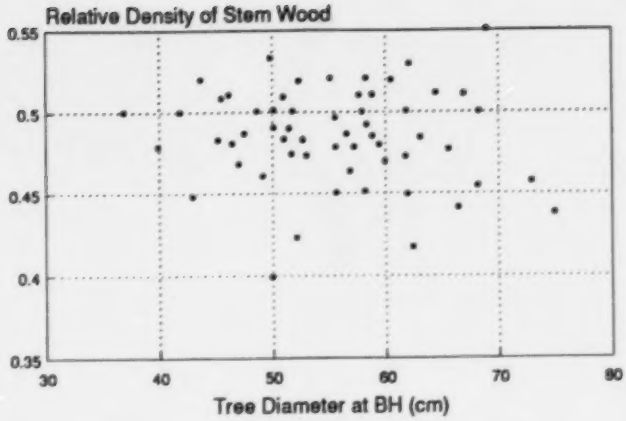


Fig. 1-10 Total stem density versus diameter at breast height for the 60 study trees

annual ring from the pith, Figure 1-11b) and the outer mature wood (40th annual ring from the pith, Figure 1-11c).

When each annual ring is segregated according to its cambial age, no relationship is found between relative density and ring width. These plots and the statistical comparisons show that the different annual rings at identical cambial age have both wide and narrow annual rings with both high and low ring density (Table 1-3). There is a negative relationship between ring width and ring density when these three annual increments are plotted together (Figure 1-11d), not because of growth rate but because of the normal within-tree pattern of ring width and ring density. Comparing growth rate effects on relative density without any regard for cambial age makes such comparisons invalid because of the normal within-tree pattern of ring width and ring density in coastal Douglas-fir, as shown in Figure 1-12. In this figure it is easy to see why there is a misconception about growth rate and relative density. The predictable within-tree relationship indicates low

Table 1-3. Ring Width and Ring Density Correlations for Three Individual Annual Rings and for their Combination Regardless of Cambial Age

Annual Ring	Number of Observations	Ring Density (g/cm^3)		Ring Width (mm)		
		Mean	s.d.	Mean	s.d.	r^2
5	60	0.47	0.053	6.70	1.33	0.096
20	60	0.52	0.058	4.78	1.44	0.165
40	53[1]	0.57	0.053	2.96	1.24	0.145
5, 20 & 40 Combined	173	0.52	0.070	4.83	2.19	0.334

1. Seven trees were younger than 40 years of age.

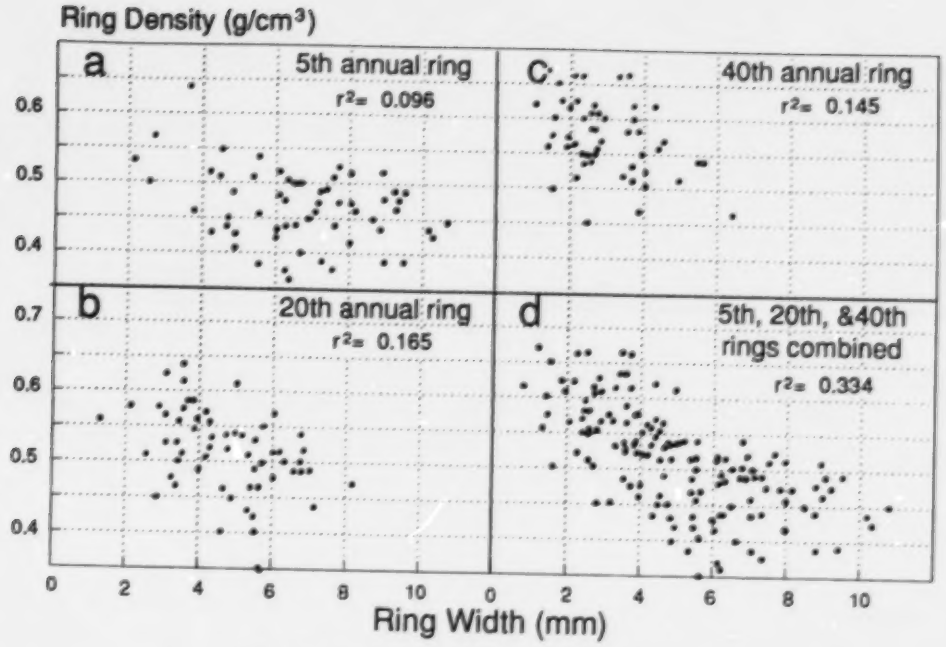


Fig. 1-11 Ring density versus ring width at several ring ages

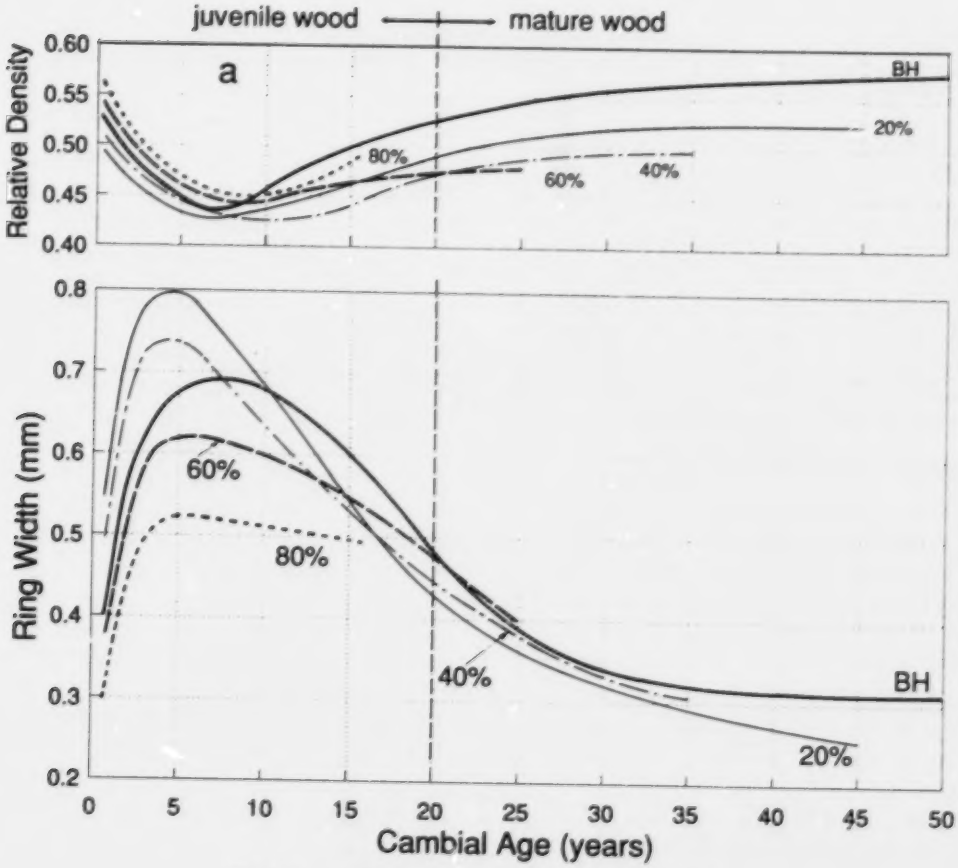


Fig. 1-12 Average ring density and ring width versus rings from pith by sampling height for the 60 study trees

density young wood with wide rings, and higher density older wood with narrow rings at all height levels. Megraw (1985, 1986) also obtained similar results for 7 year old Douglas-fir from Oregon, for 55 year old Douglas-fir from Washington, and for 36 year old loblolly pine from North Carolina. Megraw concluded that for Douglas-fir, western hemlock and the southern pines, it is tree age and height position that affects average wood properties and not growth rate.

In summary, our evidence strongly supports the following conclusions:

1. In these rapidly grown 50-year-old coastal Douglas-fir trees there is no relationship between growth rate and relative density.

2. Relatively low density wood with wide annual rings close to the pith is the result of the normal physiological influence of the crown.

Biomass Productivity Through Growth Layer Weights

Growth layer weight summaries are presented for each of six sites in Figure 1-13 as a function of age at BH. On the average, each of the 60 trees produced about 5 kilograms of wood in the 10th growth layer. The 20th, 30th, 40th, and 50th growth layers weighed about 20, 33, 41, and 56 kilograms oven-dry, respectively. Cumulatively, the average tree weighs about 1175 kilograms on an oven-dry basis at age 50.

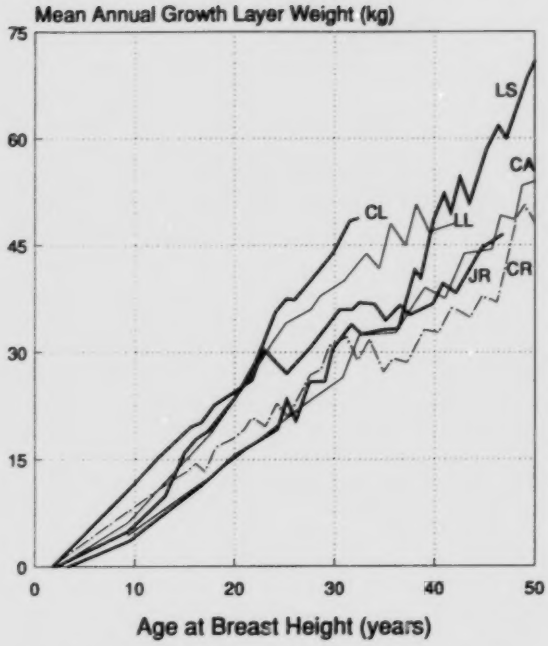


Fig. 1-13 Average growth layer weight versus age at breast height by site

The first question that comes to mind is how do these growth layer weights compare to other species at other locations? There is very little published information on this topic. Jozsa and Powell (1987) published growth layer weights for typical 110 year old dominant white spruce trees in the Boreal Forest Region in Alberta. The trees were about 25 meters tall and about 35 centimeters diameter at BH, and they produced about 6 kilograms oven-dry wood in their last (110th) growth layer. Unpublished data by Jozsa and Kellogg (1986) showed growth layer weights of about 11-12 kilograms for the last annual ring of 77 year old lodgepole pine and 95 year old white spruce from central British Columbia. For interior dry-belt Douglas-fir at age 60, the growth layer was 15 kilograms. For coastal western hemlock and Douglas-fir the last growth layer at age 55 ranged from 40 to 70 kilograms. The interior sites appeared to be much less productive than the coastal sites. Therefore, in the broader Canadian perspective, the 60 coastal Douglas-fir sample trees in this study are very efficient producers of wood.

Site-to-site growth layer weight differences in Figure 1-13 are due to a number of factors, such as stand composition, number of trees per hectare, suppression and release. For example, the Campbell River stand was thinned in 1964 at about age 32. It appears that this commercial thinning resulted in a setback for about five years, from age 33 to 37. On the average, growth layer weights were about 30 kilograms for this interval. After this setback, increasing growth layer weights are evident again from 37 to 50 years of age. To give another example, Ladysmith Douglas-fir trees were growing in association with maple and alder. The break in the trend line at age 37 to a steeper angle and markedly higher productivity rates could indicate the time when the Douglas-fir broke through the hardwood canopy and was released.

Douglas-Fir Wood Relative Density Frequency Distribution: Coastal British Columbia Perspective

The weighted average stemwood relative density frequency distribution is shown in Figure 1-14 for the 60 sample trees utilized in the basic wood property study. Relative density ranged from a low of 0.41 to a high of 0.55, and averaged about 0.49 for these 50 year old second-growth Douglas-fir trees (Table 1-4).

Although reliable information on the densities of western Canadian species was urgently required in the past to avoid the possibility of unfair discrimination in world markets, such information is almost non-existent for coastal Douglas-fir stemwood (Gonzalez, 1988). In her density survey Gonzalez (1988) calculated and reported stemwood densities for 42 trees that had been studied by Standish (1983). On the oven-dry volume basis these trees had an average relative stemwood density of 0.48 with a standard deviation of 0.058 density units. Although the average stemwood relative density is identical to the one reported for the 60 trees in this study

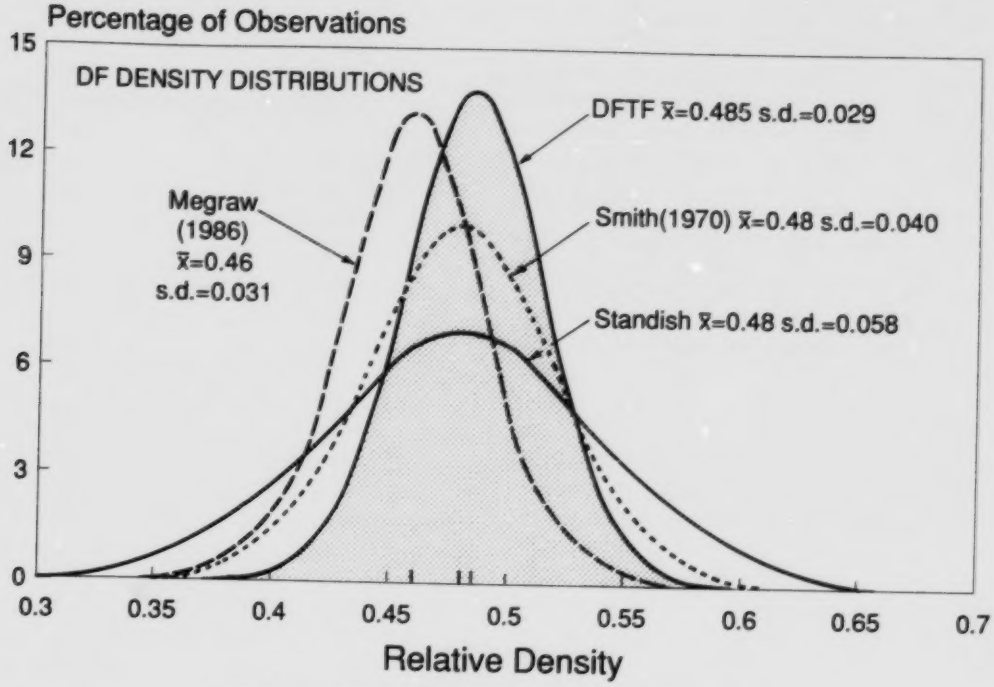


Fig. 1-14 Frequency distributions of whole stem relative density for coastal Douglas-fir

Table 1-4. Summary Statistics for 60 Sample Trees

Variable (n=60)	Mean	Min.	Max.	Standard Deviation	Coefficient of Variation (%)
Age (yrs. @ BH)	50	33	71	7.516	14.9
DBH (O.B. cm)	54.8	36.6	75.0	8.022	14.6
Height (m)	36.7	27.5	47.6	4.339	11.2
BH Disk Density	0.534	0.444	0.615	0.038	7.1
Whole Stem Density	0.485	0.405	0.550	0.029	6.1

(0.48), the standard deviation is twice as great (0.058 vs. 0.029). This implies that Standish's 42 trees were very heterogenous. Indeed they were, as his tree age statistics indicate: mean age 33 years (range 6-86).

Megraw (1986) reported the frequency distributions of relative density for disk sections at several heights for 64 Douglas-fir trees in a 55-year-old stand in Washington State, U.S.A. The results of the present study suggests that Megraw's disk density distribution from the 20 foot height level would be comparable to whole stem density. For the 64 trees in Megraw's study, at the 20 foot height level the average disk density was 0.46 (range 0.39-0.56), and standard deviation 0.031 (on oven-dry volume basis); this is quite comparable to our results. Assuming normal distribution of relative density plus the comparable mean and standard deviation of Megraw's trees suggest similar frequency distribution to the 60 trees in this study.

As a final comparison we may cite Smith's (1970) density survey results for 711 interior Douglas-fir trees. These trees were relatively slow grown with about 9 rings per centimeter (22 rings per inch). Average tree relative density was 0.48 (s.d. 0.040 on an oven-dry basis) in spite of a comparatively slow growth rate. Our study trees had about 2 rings per centimeter, therefore they grew 4.5 times faster.

From the above and from Figures 1-12 and 1-14 we may conclude that:

1. Average relative density of 0.48 for the study trees is normal in spite of rapid growth rates.
2. Because it is tree age not growth rate that dictates average stem density, different diameter trees can be compared at similar ages.
3. Stem density heterogeneity increases when trees of different ages are combined in this type of comparison.

Relative Density Comparisons Between Old-Growth and Second-Growth Douglas-Fir

One of the most common questions asked about the second-growth timber resource is, how does it compare with the old-growth timber that was harvested exclusively a few

decades ago? This is a difficult question to answer because no statistically sound data bases for Douglas-fir have been published. The literature contains only a few isolated cases documenting density variation from pith-to-bark for single logs (e.g., Kennedy and Warren, 1970). However, on a larger scale, tree averages and dimensional lumber averages have been published to provide "snapshots" of the old-growth resource.

Three Forintek publications by McGowan (1968), Jessome (1977), and Cook (1988) provide the necessary information about the relative density of old-growth Douglas-fir. The type of material tested, sample size, average relative density and standard deviation is shown in Table 1-5. A uniform species average relative density of about 0.51 to 0.52 emerged from the various sources. This suggests that as trees get older relative density does not increase indefinitely. In fact, density seems to have stabilized in the low 0.50s. For example, Kennedy and Warren (1970) reported density variations in a 500-year-old log. They found that density reached a maximum level of 0.51, at about age 50, and the tree maintained that level to about age 200. Interestingly, they also reported a density drop from age 200 to 500 from 0.51 to 0.34. Gonzalez (1987) reported whole stem densities for 42 interior Douglas-fir trees. She found whole stem density maximum values in trees of about 80 years of age. On the average, whole stem density declined in older trees, from about 0.54 for the 80-year-old trees, to about 0.45 for the 200-year-old trees.

Unfortunately, no data is available for second-growth wood from earlier times. Sampling methodology for dimensional lumber was designed to provide descriptions of the resource that was harvested at the time (McGowan, 1968; Cook, 1988). Back in the 1960s very little second-growth Douglas-fir would have been harvested and sawn to produce dimensional lumber. Even in 1988 the second-growth wood being utilized is reported to be only about 10 percent by volume.

A comparison between old-growth density values and our second-growth study trees can be made in the following way.

Table 1-5. Coastal Douglas-Fir Average Relative Density, and Standard Deviation for Old-Growth and Second-Growth Douglas-Fir

Source	Number of Samples Tested	Oven-Dry Relative Density	Standard Deviation
McGowan's Dimensional Lumber All Grades Combined	287	0.520	0.064
Jessome's Trees	78	0.510	0.061
Cook's 2 x 4 Select Structural Lumber	151	0.517	0.070
Douglas-Fir Task Force Study Trees @ Age 50	60	0.485	0.029

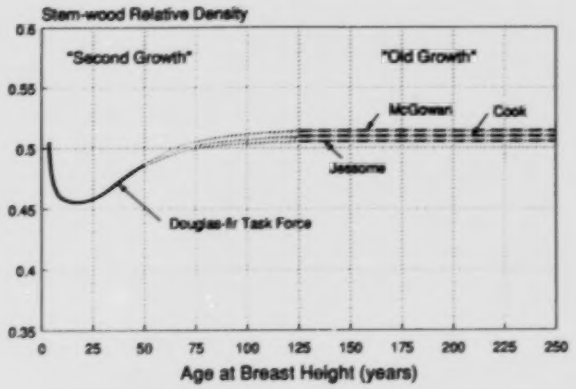


Fig. 1-15 Comparison of stem-wood relative density for old-growth and second-growth Douglas-fir

Figure 1-15 shows mean stemwood density as a function of age for the 60 trees of this study. It can be seen that from about age 15-20 there is a steady increase in stemwood relative density. Clearly, as the tree produces more dense mature wood the density of the stem increases proportionally. Extrapolating the rate of density increase, we may predict that these second-growth trees should reach stem densities above 0.50 if they are left to grow to about age 80.

In summary, the major difference between old-growth and second-growth Douglas-fir is the proportion of juvenile/mature wood. The younger the harvest age the greater the proportion of juvenile wood; this is a biological reality. As Handley (1985) pointed out there is a paradox when one considers compound interest (on the investment of stand establishment and early tending) and rotation age (as it impacts the proportion of juvenile wood). On one hand, from the financial return perspective, the forest manager is pressured to harvest the managed forest at an early age. On the other hand, from the wood quality perspective, the forest manager would be advised to lengthen the rotation. In the final analysis he should also consider stand productivity.

Conclusions

This report describes the results of X-ray densitometric analysis of sixty 50-year-old Douglas-fir trees from Vancouver Island. Special attention was focussed on the extent and distribution of juvenile wood, and on the effect of cambial age and position in the stem on the relative density of wood.

From a stand management perspective our attention was focussed on describing juvenile wood characteristics and distribution, based on relative density. Tree productivity was examined as a function of age and was compared to other species. From the utilization perspective of wood and fiber, relative density variation was examined and compared within

annual rings, within trees, between trees, and to the degree possible, second-growth to old-growth.

The present sampling plan does not permit statistically sound site-to-site comparisons. The data base generated here may ultimately be used as input variables in more refined growth prediction models and will permit us to test various forest management strategies that will influence the volume of the juvenile wood core selected for both dimensional lumber and pulping quality.

The results of this study suggest that the lack of uniformity in relative density within a tree is a natural consequence of tree growth and the influence of the live-crown. Non-uniformity is due to the change from juvenile to mature wood both radially and axially. There is no relationship between growth rate and relative density at fixed cambial ages. Tree-to-tree variation in average stemwood density is important, even with identical site averages, because it is the lower fifth percentile of strength, and indirectly of density, which could determine the machine stress rated grade of dimensional lumber. Therefore, in theory, a site with a homogenous density distribution would produce wood rating higher in strength than a heterogenous one, other variables being equal.

Tree-to-tree average stemwood density variation was about 30 percent for the 60 trees. At each of the sampling locations the 20 percent height disks had an average relative density that was within 0.01 density unit of whole stem density. Therefore, if whole stem density measurements are required for coastal Douglas-fir trees at this age, the 20 percent height position disks could provide reliable estimates of stem density.

It should be pointed out that these 60 trees do not represent the resource presently being harvested. What we feel the sample trees do represent is the type of trees that will come from rapidly grown, managed coastal Douglas-fir stands.

It is clear from this study that there are a number of ways in which the average relative density of the harvested resource can be controlled. One of the most basic of these is simply increasing the rotation age and therefore increasing the proportion of mature wood. A second means would be to reduce the growth rate in the early part of the rotation period when juvenile wood is being produced in the lower stem, and then stimulating the growth rate during the latter part of the rotation. Another means would be to stimulate growth rate from an early age, but combine that strategy with pruning. Multiple pruning entries which would keep the juvenile knotty core at a minimum would maximize the production of clear mature wood. A final method of control would be tree improvement. The great degree of tree-to-tree variation in relative density, and the known heritability of this property, offers a potential for control which should be more thoroughly investigated. Obviously, the economics of all these management strategies will have to be evaluated.

References

Bastien, J.Ch., B. Roman-Amat, and G. Vonnet. 1985. Natural variability of some wood internal traits of coastal Douglas-fir in a French progeny test. Implications on breeding strategy. Paper presented at the IUFRO S2.02.05-W.P. meeting in Vienna, Austria. Unpublished paper. 18p.

Bendtsen, B.A. and J. Senft. 1986. Mechanical and anatomical properties in individual growth rings of plantation-grown eastern cottonwood and loblolly pine. Wood and Fiber Sci. 18(1):23-38.

Cook, J.A. 1988. The establishment of end-product based criteria for the evaluation of wood density in tree improvement programs. CFS Contract Report No. 4-55-12X-156. Forintek Canada Corp., Vancouver, BC. 13p.

Duff, G.H. and N.J. Nolan. 1953. Growth and morphogenesis in the Canadian forest species. I. The Control of cambial and apical activity in *Pinus resinosa* Ait. Can. J. Bot. 31:471-513.

Echols, R.M. 1972. Product suitability of wood. . .determined by density gradients across growth rings. Research Note, PSW-243. USDA Forest Service, Berkeley, CA. 6p.

Fritts, H.C. 1976. Tree Rings and Climate. New York: Academic Press.

Gonzalez, J.S. 1987. Wood density of tree species in British Columbia. Contract Report No. 01K45-5-0353/01-SG. Forintek Canada Corp. Vancouver, BC. 27p.

Gonzalez, J.S. 1988. Wood density of Canadian tree species. Contract Report No. 5559X651. Forintek Canada Corp. Vancouver, BC. 49p.

Handley, D.L. 1985. The new forest and the optimum tree. Canadian Forest Industries. November, p.21-23.

Heger, L., M.L. Parker, and R.W. Kennedy. 1974. X-ray densitometry: A technique and an example of application. Wood Sci. 7(2):140-148.

Jessome, A.P. 1977. Strength and related properties of woods grown in Canada. Forestry Technical Report 21. Forintek Canada Corp., Ottawa, ON. 37p.

Johnson, J.A. 1986. Wood quality and its relationship to uses, grades, and prices: past, present, and future. In: Douglas-fir: Stand Management for the Future. C.D. Oliver, D.P. Hanley and J.A. Johnson, eds. University of Washington, Institute of Forest Resources, Contribution No. 55. Seattle, WA. p.143-148.

Jozsa, L.A. and R.M. Kellogg. 1986. An exploratory study of the density and annual ring weight trends in fast-growth Coniferous woods in British Columbia. CFS Contract Report No. 02-80-55-017. Forintek Canada Corp., Vancouver, BC. 43p.

Jozsa, L.A. and R.M. Myronuk. 1986. Direct reading X-ray densitometer. CFS Contract Report No. 55-12-001. Forintek Canada Corp., Vancouver, BC. 15p.

Jozsa, L.A., J.E. Richards, and S.G. Johnson. 1987. Calibration of Forintek's direct reading X-ray densitometer. CFS Contract Report No. 55-12-104. Forintek Canada Corp. Vancouver, BC. 16p.

Jozsa, L.A., and J.M. Powell. 1987. Some climatic aspects of biomass productivity of white spruce stem wood. Can. J. For. Res. 17:1075- 1079.

Kennedy, R.W. 1970. Specific gravity of early-and-late-flushing Douglas-fir trees. Tappi 53:1479-1481.

Kennedy, R.W. and W.G. Warren. 1970. Within tree variation in physical and chemical properties of Douglas-fir. In: Second World Consultation on Forest Tree Breeding, Vol. 1. Washington, DC. FAO, Rome. p.393-417.

Larson, P.R. 1969. Wood Formation and the Concept of Wood Quality, Bulletin No. 74. Yale University, School of Forestry. New Haven, CT. 54p.

McGowan, W.M. 1968. Parallel-to-grain tensile properties of visually graded 2x6-inch Douglas-fir. Information Report VP-X-46. Forintek Canada Corp. 48p.

Megraw, R.A. 1985. Wood Quality Factors in Loblolly Pine. TAPPI Press. Atlanta, GA. 88p.

Megraw, R.A. 1986. Douglas-fir Wood Properties. In: Douglas-fir: Stand Management for the Future, C.D. Oliver, D.P. Hanley and J.A. Johnson, eds. University of Washington, Institute of Forest Resources, Contribution No. 55. Seattle, WA. p.81-96.

Mork, E. 1928. Quality of pine wood, with special reference to its use as pulp. Papier J. 16:40-44.

Olesen, P.O. 1976. The interrelationship between basic density and ring width of Norway spruce. Forstl. Forsogsv. Danm. 34:339- 359.

Panshin, A.J. and C. deZeeuw. 1980. Textbook of Wood Technology. 4th ed. McGraw-Hill. New York. 722p.

Parker, M.L. R.D. Bruce, and L.A. Jozsa. 1980. X-ray densitometry of wood at the W.F.P.L. Tech. Rep. No. 10. Forintek Canada Corp., Vancouver, BC. 18p.

Pearson, R.G., and B.E. Ross. 1984. Growth rate and bending properties of selected loblolly pines. Wood and Fiber Sci. 16:(1)37-47.

Richardson, S.D. 1961. Biological basis for sampling in studies of wood properties. Tappi 44(12):170-173.

Smith, W.J. 1970. Wood density survey in western Canada. Report VP-X-66. Forintek Canada Corp., Vancouver, BC. 29p.

Standish, J.T. 1983. Development of a system to estimate quantity of biomass following logging in British Columbia forests to specified recovery criteria. Report on ENFOR Proj. No. 7952, D.S.S. Contract No. OSB80-00001. Talisman Land Resource Consultants, Vancouver, BC. 1159p.

Taylor, F.W., E.I.C. Wang, A. Yanchuk and M.M. Micko. 1982. Specific gravity and tracheid length variations of white spruce in Alberta. Can. J. For. Res. 14:181-185.

CHAPTER 2

Juvenile-Mature Wood Transition

C.M. Di Lucca *Faculty of Forestry, University of British Columbia*
Currently: Foryx Forest Consultants Ltd.

Introduction

Relative density is one of the most important physical indicators of wood quality. This is due to its high correlation to pulp yield, paper-making properties and strength properties of lumber (Barefoot *et al.*, 1970; Gonzalez and Kellogg, 1978; Kellogg, 1982).

The Tree and Stand Simulator (TASS) developed by Mitchell (1975) and the Ministry of Forests of British Columbia (Mitchell and Cameron, 1985) models the growth and yield of second-growth coastal Douglas-fir under different management conditions (Chapter 13). This is a biologically oriented model that simulates the growth of tree crowns and individual annual rings along the stem. In order to incorporate a wood quality concept into TASS it is necessary to investigate when and where the transition between juvenile and mature wood occurs.

Consequently, this project tests and analyzes the hypothesis that: The relative density transition from juvenile to mature wood in individual annual rings of second-growth coastal Douglas-fir occurs at the base of the live crown.

Literature Review

Influence of the Crown on Wood Formation

The hormonal and the secondary wall thickness regulation hypotheses (Wareing, 1958; Larson, 1963, 1969) state that earlywood and latewood tracheid formations are correlated to photosynthate availability and presence of auxin. These crown formed products determine the rate of cambial initial cell division and the degree of differentiation of the cambial derivatives. Within the crown, the most vigorously active live branches will regulate wood formation by a steady production of photosynthates and auxins. These branches are characterized by complete growth increments or annual rings along their length, which form an active union with the main stem.

As the branches start to compete for light and become older and longer, their vigor, given by the capacity of producing photosynthates and auxins, gradually decreases (Larson, 1969). In addition, the increase of the translocation pathways to the main stem, due to the increase in branch length, also leads to a decrease in the current shoot length from the apex to the base of the live crown and from the tip to the base of the branch (Fraser, 1962; Forward and Nolan, 1964).

The decrease in branch vigor is followed by a period of senescence which starts at the lower crown branches. At this time the contribution of these branches to wood formation gradually decreases, leading to the formation of incomplete or absent annual rings at the branch base (Andrew and Gill, 1939; Reukema, 1959, 1961; Reeb, 1984). These senescent branches, which are still attached to the main stem, no longer have any contact with the main translocation pathways in the tree, resulting in diminishing contribution to wood formation until branch death occurs. Larson (1969) concluded that major changes in wood formation and quality occur below the living crown, or below the most active branches of the crown. The crown size or crown length, therefore, has important implications not only in wood formation, but also in forest management strategies.

The age of the tree also has an influence on wood formation. A young tree with a high percentage of the stem covered with active live branches will produce wide annual rings with a high proportion of earlywood tracheids. This is explained by the prolonged influence of the apical meristems on the cambial regions in the active live crown. As the tree grows older and the crown rises, the proportion of latewood tracheids in the annual rings below the live crown gradually increases.

Consequently, two characteristic wood zones can be differentiated within the tree stem as a function of distance from the active live branches and age from the pith. The first zone, called juvenile wood, forms a central core of wood around the pith extending from the base to the apex of the tree. The second, called mature wood, is formed around the juvenile wood core and below the living crown.

Juvenile and Mature Wood

Universal definitions of the terms juvenile and mature wood have not been agreed upon, although such terms are adequate in denoting the types of wood produced in relation to crown proximity and number of annual rings from the pith (age). Several authors have defined juvenile and mature wood from different points of view. For instance, when considering the

juvenile and mature wood stem positions in a tree, juvenile wood has been called core, inner, or pith-associated wood, and mature wood has been called exterior, outer or non-pith-associated wood (Perry and Wang, 1958; Zobel *et al.*, 1959; Moody, 1970).

Juvenile wood has been called immature or youthful wood and mature wood has been called old or adult wood, on the basis of their respective physiological stages of maturity (Rendle, 1958, 1959, 1960). Juvenile wood has been called crown-formed wood because it is formed inside the living crown, and mature wood has been called stem-formed wood due to its formation outside of the living crown (Trendelenburg, 1935; Cooper, 1960; Brunden, 1964; Larson, 1969, 1973).

The size of the juvenile wood core generally depends upon the growth rate, regardless of the species. Silvicultural practices such as fertilization, irrigation and thinning will temporarily decrease crown recession and increase crown vigor, growth rate and, as a result, the size of the juvenile wood core (Bendtsen, 1978; Briggs and Smith, 1986; Megraw, 1985; Oliver, 1986).

The proportion of the juvenile wood core in the stem is a function of the species, number of annual rings from the pith and distance from the active live crown (Paul, 1960; Bendtsen, 1978). This proportion tends to be high in early harvested trees and in open-grown trees. Increasing crown recession by delaying the harvesting age of stand-grown trees will decrease the juvenile wood proportion at harvest age. An abrupt change from juvenile to mature wood can also be achieved by pruning the live and vigorous lower branches in the crown (Marts, 1949; Gerischer and De Villiers, 1963; Smith, 1968; Larson, 1965, 1969; Cown, 1973; Polge *et al.*, 1973; Plumptre and Austin, 1978). It is evident that the growth and development of the active live crown as a function of age will determine the quantity and quality of juvenile and mature wood in the stem.

Determination of the transition zone from juvenile to mature wood is critical for setting relative proportions, and important in defining wood quality and timber value. This determination can be difficult, however, because as juvenile wood matures, its properties change only gradually and often erratically. These changes also differ according to species and wood properties selected for analysis. For example, the mechanical properties and relative density of wood generally indicate maturity earlier than tracheid length and microfibril angle (Bendtsen, 1978; Megraw, 1985; Bendtsen and Senft, 1986).

Some species of spruce (*Picea* spp.), fir (*Abies* spp.) and cypress (*Cuppressus* spp.) are characterized by an indistinct juvenile-mature wood transition zone. Therefore, the differences in properties between juvenile and mature wood are difficult to observe (Zobel, 1984). In contrast, Douglas-fir and most hard pines, such as loblolly pine, slash pine and Caribbean pine, show a more distinct juvenile-mature wood transition zone. Di Lucca (1987) described some subjective and objective methods utilized by several authors to define the transition zone between juvenile and mature wood.

Juvenile and mature wood must be considered as two different categories within the same tree because of their fundamental differences in wood quality (Panshin and de Zeeuw, 1980). Such differences are determined primarily by tracheid anatomical structure and chemical composition, and secondarily by the derived physical wood properties (Chapter 1).

Materials and Methods

A total of 24 trees were sampled in order to test the project hypothesis (Tables 2-1 and 2-2). Thirteen of these trees were stand-grown, two were plantation-grown, two were pruned and seven were open-grown.

Twelve stand-grown trees, with breast-height-age ranging from 33 to 63 years, were selected from the original sample sites and one 21 year old tree was selected from the University of British Columbia Research Forest at Haney. The two 37 year old plantation-grown trees were selected from plantations growing on soils of high (marine clay) and low (gravel outwash) productivity located west of Campbell River. The pruned trees of 51 and 45 years of age were sampled from the University of British Columbia Research Forest. These trees were approximately 15 centimeters diameter at breast height and 14 meters tall when the lower one-third of the live crown was pruned to a height of 4 to 5 meters in 1954. The seven open-grown trees, with breast-height-age ranging from 24 to 70 years, were selected on medium productivity sites from the Lake Cowichan region.

Stump age, total height and internodal distances were measured for each stand-grown and pruned tree before sectioning the stem into five cross-sectional disks sampled from breast height, and positions 20, 40, 60 and 80 percent of total tree height. A total of 12 cross-sectional disks were cut from each open-grown tree, one at 30, 70 and 130 centimeters, and nine others at one-tenth intervals of total height.

To assess the actual crown characteristics, crown cover, live branches and height to base of the live crown were measured as follows. The crown cover, or ground area covered by the vertical projection of each crown, was measured before each tree was felled, using a metric tape and a Suunto clinometer with a 90 degree scale. An average crown radius was estimated from six to seven crown radii measurements taken every 45 degrees around the perimeter of the crown and towards competing trees (Table 2-1).

The length and height positions of two live branches of similar diameter from opposite sides of every second whorl were measured from each stand-grown tree . The height to base of the live crown was determined by measuring the distance from the ground to the lowest whorl that had three or more live branches. In addition, an average crown height was calculated

Table 2-1. Tree Characteristics for Stand-Grown and Pruned Trees

Sample Tree No.	Location	Height (m)	Age (BH)	Crown[1] Length (m)	Crown[1] Base Height (m)	Crown[1] Base Age	Crown Length[2] Ratio	Average[3] Crown Length (L) (m)	Average[3] Crown Height (m)	Average[3] Crown Age	Crown Radius (BL) (m)	Coeff. Values (b)
1A5	Ladysmith	37.0	56	14.8	22.2	28	0.40	14.3	22.7	27	4.65	3.952
1A7	Ladysmith	37.0	51	13.6	23.4	29	0.36	10.0	27.0	23	4.68	4.956
1B6	Cassidy	44.7	53	21.9	22.8	28	0.48	13.0	31.7	17	4.23	3.806
1B11	Cassidy	36.1	63	15.3	20.8	35	0.42	15.1	21.3	34	4.40	3.625
1C1	Campbell River	40.0	54	15.9	24.1	29	0.39	13.8	26.4	26	3.61	3.612
1C6	Campbell River	38.0	53	13.2	24.8	24	0.34	11.1	26.9	19	3.70	3.701
1D5	Lake Cowichan	32.0	33	16.9	15.1	20	0.52	12.0	19.9	13	3.47	3.262
1D6	Lake Cowichan	29.5	35	11.3	18.2	16	0.38	8.5	21.0	13	3.40	3.966
1E3	Lizard Lake	35.0	43	17.9	17.1	21	0.51	13.2	22.2	17	4.01	3.588
1E8	Lizard Lake	36.0	47	14.4	21.6	25	0.40	8.8	27.2	17	3.66	4.204
1F7	Jordan River	41.5	53	18.1	23.4	28	0.43	7.7	33.8	15	3.24	4.080
1F10	Jordan River	39.0	52	14.2	24.8	29	0.36	8.7	30.3	21	2.91	3.362
RF1	Haney	23.3	21	14.3	9.0	12	0.61	8.1	15.2	6	2.64	3.213
RF2	Haney (pruned)	31.7	51	21.0	10.7	39	-	-	-	-	-	-
RF3	Haney (pruned)	29.7	45	18.1	11.6	33	-	-	-	-	-	-
CR1	Hart	16.8	37	6.7	9.4	22	0.40	3.9	12.8	16	1.48	3.239
CR2	Memekay	31.5	35	12.8	18.7	19	0.40	5.6	25.9	9	2.80	4.420
Averages[4]		34.5	46	14.7	19.7	24	0.42	10.2	24.2	18	3.50	3.799

1. Base of the live crown height observed as the lowest part of the crown with three or more live branches.
2. Crown length ratio = crown length / tree height.
3. Average crown height estimated as tree height minus L, where L is given by:

$$L = c\,(e^{BL/(bd)} - 1)$$

L = crown length or distance from terminal leader to branch base
c = coefficient describing the shape of the crown (estimated for Douglas-fir as 6.1)
BL = crown radius
b = coefficient relating branch growth to height growth
d = coefficient compensating for branch crooks (estimated for Douglas-fir as 0.975)
e = 2.71828

4. Overall averages not including pruned trees RF2 and RF3.

Table 2-2. Tree Characteristics for Open-Grown Trees

Sample Tree No.	Location	Height (m)	Age BH	Crown Length (m)	Crown Base Height (m)	Crown Length Ratio
CO1	Lake Cowichan	26.2	44	22.9	3.3	0.87
CO2	Lake Cowichan	31.8	38	30.8	0.9	0.97
CO3	Lake Cowichan	24.6	34	23.9	0.7	0.97
CO4	Lake Cowichan	32.7	63	23.0	6.6	0.70
CO5	Lake Cowichan	33.7	70	25.7	8.0	0.76
CO6	Lake Cowichan	22.1	38	20.5	1.6	0.92
CO7	Lake Cowichan	15.2	24	14.7	0.4	0.97
Averages		26.6	44	23.5	3.1	0.88

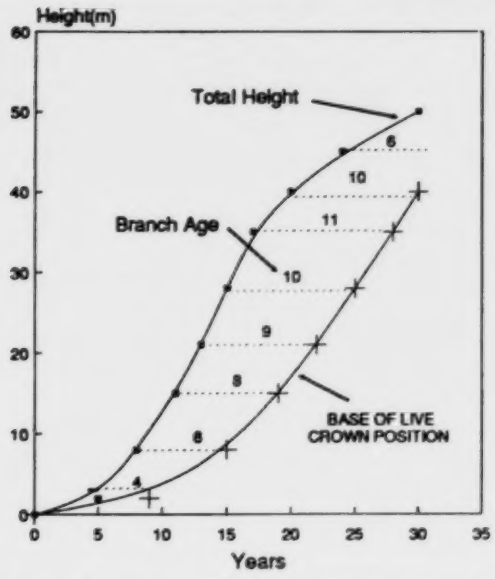


Fig. 2-1 Use of relationship between total height and branch age to estimate the base of live crown positions at earlier tree ages

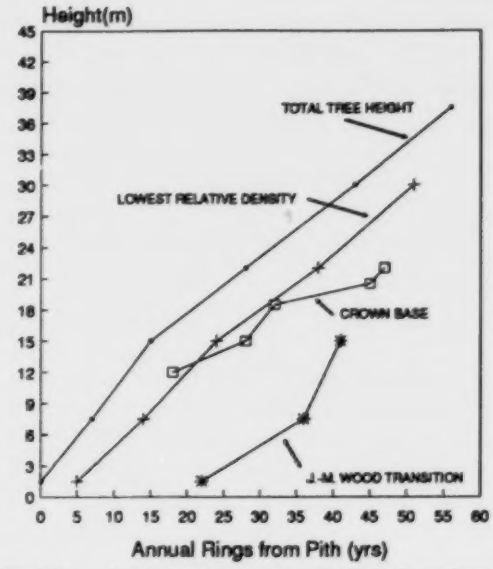


Fig. 2-2b Height versus annual rings from pith for total tree height, lowest relative density height, crown base height and juvenile-mature wood transition height for tree 1A5

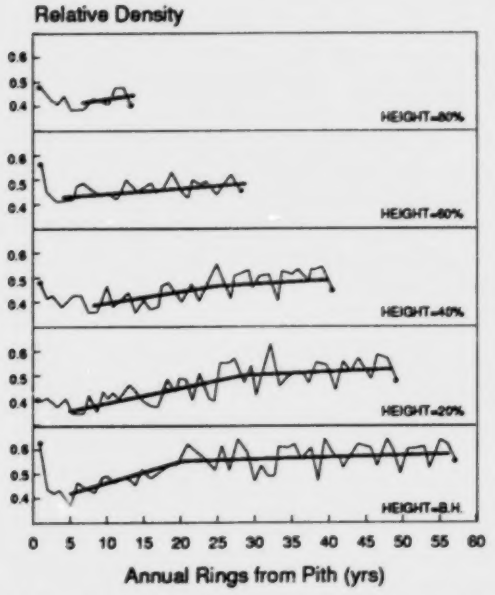


Fig. 2-2a Simple and segmented linear regression models fit to pith to bark relative density profiles for tree 1A5

as a function of the average crown radius, which represented the maximum length of the branches located at the widest part of the crown in stand-grown trees (Mitchell, 1975).

To investigate the development of the crown over time in stand-grown trees, two representative dead branches or branch stubs were collected from every second or third branch whorl. Each branch was examined to determine the number of annual rings at the base, which represented the age at which the branch stopped producing annual rings. Cross-sectional disks of one centimeter thickness were cut from each branch base, labelled and sanded. The annual rings in each branch disk were counted and recorded using a low power stereoscopic microscope. The number of annual rings in each branch disk and the corresponding whorl height position were utilized to determine the approximate position of the base of the live crown as shown in Figure 2-1.

It was decided that the radial pattern of relative density would be used to determine at what age the transition from juvenile to mature wood took place at any height position. X-ray densitometric techniques were used to determine these patterns of relative density.

X-Ray Densitometric Analysis

For the x-ray densitometric evaluation, a total of 169 cross-sectional disks (17 trees five sample heights and seven trees 12 sample heights) of 8 to 16 centimeters thick, were sampled. On each disk, two average radii sections at least 90 degrees apart were measured and labelled, avoiding knots, resin pockets and compression wood. The average radii were first cut into strips of one centimeter thick and 10 centimeters wide. They were then re-cut into smaller sample strips, five millimeters wide in the tangential direction and six millimeters thick along the grain, resembling increment cores. The wood sample strips were utilized for x-ray densitometric

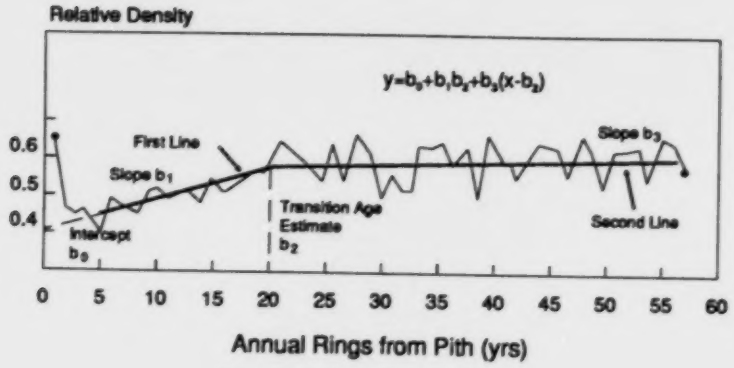


Fig. 2-3 Segmented regression model

analysis following the procedures explained in detail by Parker and Jozsa (1973) and by Parker et al. (1973).

A total of 326 wood core radii were scanned using the above procedure. The relative density values were expressed on an oven-dry volume and weight basis. Annual pith to bark relative density profiles (average relative density of two core radii per sample section) were plotted to determine the relative density variation patterns as a function of number of annual rings from the pith and height position on the stem of each sample tree, as shown in Figures 2-2a and 2-2b for tree 1A5.

Juvenile-Mature Wood Transition Determination

After plotting the relative density profiles of each sample section, the plots were visually examined to find the lowest relative density value and a possible juvenile-mature wood zone based on the shape of the profile. Two categories of profiles were identified. The first category included the relative density profiles that showed fairly constant relative density values from the pith to bark, without a clear definition of transition zone. In this case, a simple linear regression model was fitted to each profile, starting from the lowest relative density value outwards, and it was assumed that the profile represented juvenile wood entirely.

The second category included the profiles that showed an initial decrease in relative density in the first annual rings from the pith, followed by a gradual linear increase for a certain number of rings, then a final leveling off outwards. This relative density variation pattern indicated the possible evidence of a transition zone in the profile. To determine such transition zone, a segmented regression analysis of each relative density profile was done as described below (Hudson, 1966; Draper and Smith, 1981).

1. A segmented regression model, which combines two linear segments, was fitted to each profile starting at the lowest relative density value as shown in Figure 2-3. The model utilized was:

$$\hat{y} = b_0 + b_1 b_2 + b_3 (x - b_2)$$

where:

$\hat{y}$ = predicted value (relative density)
b_0 = intercept of first line segment
b_1 = slope of first line segment
b_2 = transition age estimate (number of annual rings from the pith).
b_3 = slope of second line segment
x = independent variable (number of annual rings from the pith)

2. The model that afforded the best fit was determined by minimizing the total residual sum of squares of every possible division of points between the first and the second segment. This method is called the Least Squares Line of Best Fit and is given by:

$$\sum_{i=1}^{n} e^2 i = \sum_{i=1}^{n} (yi - \hat{y}i)^2$$

where:

$\sum_{i=1}^{n} e^2 i$ = residual sum of squares
yi = observed values (relative density)
$\hat{y}i$ = predicted values (relative density)

3. The constraints of this procedure were that the first segment must start at the lowest relative density data point and that the intersection point between the two segments must be between two consecutive annual rings that split the data set.

4. The point of intersection between the two linear segments was identified to determine the age at which the transition from juvenile to mature wood occurred.

5. To verify the need for a segmented regression analysis, a statistical "F" test was done, calculating the ratio between the mean sum of squares residual value of a simple linear regression model and that of a segmented regression model, both fitted to the same profile (Hinkley 1969).

Table 2-3. Summary of the Distribution of Relative Density Profiles Without Juvenile-Mature Wood Transition in Stand-Grown Trees

Sample Section	Number of Sections	Height (m)				Juvenile Wood Number of Annual Rings (years)			
		Mean	s.d.	Max.	Min.	Mean	s.d.	Max.	Min.
B.H.	1	1.3	-	1.3	1.3	21	-	21	21
20%	1	4.5	-	4.5	4.5	17	-	17	17
40%	6	10.8	3.31	14.4	5.1	24	7.37	33	13
60%	15	20.5	4.26	25.8	9.9	22	6.50	31	8
80%	15	27.6	5.83	36.1	13.3	12	4.58	19	4
All Sections	38	20.9	8.58	36.1	1.3	19	7.45	33	4

When the "F" ratios calculated were greater than the "F" values tabulated by Pearson and Hartley (1954) the segmented regression model was chosen to determine the juvenile-mature wood transition zone. When the "F" ratios calculated were lower than the "F" values tabulated, the simple regression model was chosen and the juvenile-mature wood transition zone could not be determined. In this case, it was assumed that the relative density profile represented juvenile wood entirely.

6. The determination of the transition zone was checked against the corresponding profile to ensure that the regression model used was the most reasonable choice with respect to the data.

After determination of the juvenile-mature wood transition age for each relative density profile, relationships between age and tree height position of both transition zone and base of the live crown were established.

Results and Discussion

Table 2-1 gives a summary of the stand-grown and pruned tree characteristics. The plantation-grown and stand-grown trees were dominant and codominant with ages at breast height ranging from 21 to 63 years, diameters at breast height from 19.8 to 68.2 centimeters and total heights from 16.8 to 44.7 meters. For the open-grown trees, the ages at breast height ranged from 24 to 70 years, diameters from 29.8 to 86.3 centimeters and total heights from 15.2 to 33.7 meters (Table 2-2). The stand-grown trees were analyzed separately from the open-grown and the pruned trees.

Stand-Grown Trees

A total of 75 relative density profiles (15 trees, five sample height positions per tree) were investigated in order to detect transition zones between juvenile and mature wood. The profiles were divided into two categories based on the configuration of the data points pertaining to relative density and number of annual rings from the pith.

The first category included 38 profiles characterized by having no clear definition of a juvenile-mature wood transition zone. In general, these profiles showed an initial decrease in relative density from the pith to a point within the fourth through thirteenth annual rings, followed by a gradual increase, decrease or leveling off outwards. To illustrate such trends, simple linear regression models were fitted to each profile, starting from the lowest relative density value outwards, assuming that they represented juvenile wood entirely (Figure 2-2a, sections 60 and 80 percent).

Table 2-3 shows a summary of the distribution and characteristics of these profiles among sample heights. The average number of annual rings was 19, ranging from 4 to 33, and the average section height was 20.9 meters, ranging from 1.3 to 36.1 meters. It can be seen that about 80 percent of the cases for which no evidence of juvenile-mature wood transition zone was found were at sections 60 and 80 percent of total height. In 15 percent of the cases no transition was found at 40 percent of total height. Only in 5 percent of the cases was no transition found at sections sampled at breast height and 20 percent of total height, corresponding to the younger sampled tree (RF1).

From the above, it is concluded that mature wood and therefore the juvenile-mature wood transition zone, was not present in sections sampled above 40 percent of total height, nor in lower sections containing few annual rings from the pith.

The second category comprised relative density profiles which gave evidence of a transition zone. These profiles, in general,

Table 2-4. Transition Determination by Comparing Simple Against Segmented Linear Regression Models on Relative Density Profiles

Sample Tree No.	Location	Section Height (m)	Juvenile-Mature Wood Transition Age (years)	Simple Linear Model 1		Segmented Linear Model 2		"F" Value Model 1 / Model 2	"F" Prob. P > F
				D.F.	Mean Square ($\times 10^{-3}$)	D.F.	Mean Square ($\times 10^{-3}$)		
1A5	Ladysmith	1.3	22	50	2.081	48	1.623	1.281	0.20
		7.5	28	41	1.971	39	1.857	1.061	0.42
		14.9	25	23	1.660	21	1.480	1.121	0.40
1A7	Ladysmith	1.3	19	41	2.058	39	1.468	1.401	0.14
		7.2	24	35	2.609	33	1.743	1.496	0.14
		15.1	24	31	1.303	29	0.841	1.548	0.10
1B6	Cassidy	1.3	16	44	1.302	42	1.129	1.153	0.32
		8.5	17	35	0.751	33	0.666	1.128	0.37
		17.2	18	24	0.564	22	0.542	1.055	0.40
1B11	Cassidy	1.3	32	56	1.738	54	1.247	1.394	0.11
		7.1	25	50	1.373	48	0.863	1.590	0.05
		14.2	16	41	1.176	39	1.023	1.150	0.34
1C1	Campbell River	1.3	19	47	1.182	45	0.915	1.292	0.19
		8.0	25	41	0.868	39	0.597	1.454	0.02
		16.0	29	32	0.482	30	0.463	1.042	0.42
1C6	Campbell River	1.3	15	47	2.258	45	1.980	1.141	0.33
		7.6	35	41	2.247	39	1.813	1.239	0.26
		15.2	26	31	2.284	29	1.006	2.270	0.00
1D5	Lake Cowichan	1.3	19	30	0.861	28	0.844	1.020	0.43
		6.4	20	23	0.759	21	0.712	1.070	0.44
1D6	Lake Cowichan	1.3	17	30	1.015	28	0.878	1.156	0.35
		5.9	15	24	0.661	22	0.542	1.220	0.31
1E3	Lizard Lake	1.3	28	32	1.069	30	0.985	1.085	0.41
		7.1	26	25	0.785	23	0.762	1.031	0.47
		14.0	11	19	0.405	17	0.293	1.378	0.25
1E8	Lizard Lake	1.3	34	41	1.055	39	0.930	1.134	0.35
		7.2	26	31	1.220	29	1.019	1.197	0.32
1F7	Jordan River	1.3	25	45	1.633	43	0.801	2.037	0.01
		8.3	25	39	1.086	37	0.422	2.573	0.00
		16.4	24	28	1.418	26	0.852	1.664	0.10
1F10	Jordan River	1.3	24	49	1.338	47	0.985	1.358	0.15
		7.8	22	39	1.465	37	1.023	1.425	0.14
		15.9	15	35	0.557	33	0.48	1.244	0.27
CR1	Hart	1.3	20	28	1.576	26	1.331	1.183	0.25
		3.3	19	22	1.905	20	1.019	1.873	0.07
CR2	Memekay	1.3	23	24	0.930	22	0.797	1.166	0.32
		6.4	13	23	0.866	21	0.798	1.087	0.42
CO4	Lake Cowichan	0.3	32	60	1.134	58	0.639	1.772	0.02
		0.7	28	53	1.233	51	0.635	1.940	0.01
		1.3	26	53	1.396	51	0.563	2.347	0.00
		3.2	22	50	1.196	48	0.631	1.896	0.02
		6.5	14	45	1.023	43	0.850	1.166	0.30
CO5	Lake Cowichan	0.7	48	48	1.045	46	0.776	1.346	0.15
		3.8	32	48	1.229	46	1.164	1.055	0.42

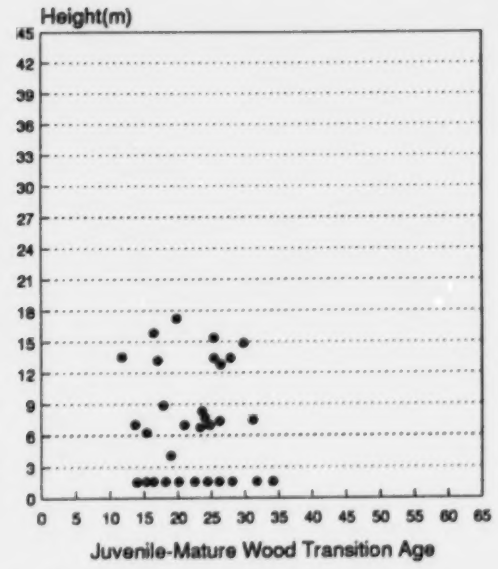


Fig. 2-4 Height in stem versus juvenile-mature wood transition age

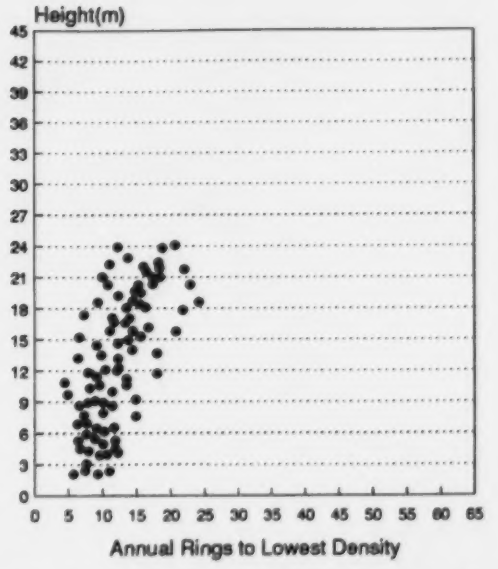


Fig. 2-5 Height in stem versus number of annual rings at the lowest relative density value in the pith to bark profile

Table 2-5. Summary of the Distribution of Relative Density Profiles Which Showed Juvenile-Mature Wood Transition

Sample Section	Number of Sections	Height (m)				Total Number of Annual Rings				Juvenile-Mature Wood Transition Age (years)			
		Mean	s.d.	Max.	Min.	Mean	s.d.	Max.	Min.	Mean	s.d.	Max.	Min.
B.H.	14	1.3	-	1.3	1.3	48	9.33	63	33	23	5.77	34	15
20%	14	7.0	1.03	8.5	3.3	41	8.44	53	27	23	5.72	35	13
40%	9	15.4	1.04	17.2	14.0	37	5.40	45	26	21	6.05	29	11
All Sections	37	6.9	5.59	17.2	1.3	43	9.07	63	26	23	5.71	35	11

showed an initial relative density decrease in the first annual rings from the pith, followed by a gradual increase over several additional annual rings, then a final leveling off outwards. A total of 37 profiles from 14 trees were investigated in this section. Segmented linear regression models, starting at the lowest relative density value, were fitted to these profiles in order to determine the juvenile-mature wood transition zone (Figure 2-2a, sections BH, 20 and 40 percent). The point of intersection between the two linear segments corresponding to the segmented model was identified as the age at which the transition from juvenile to mature wood occurred.

Table 2-4 gives a summary of the transition ages of each tree sample section, determined by using segmented linear regression models. To verify the need of such models, the "F" ratio of the mean sum of squares residual value of a simple linear regression model to that of a segmented model, both fitted to each relative density profile, was calculated for each sample section. In all cases, the calculated "F" ratios were greater than one, indicating that the segmented regression model showed a smaller sum of squares residual value, and thus a better data fit. The probability level at which the calculated "F" ratios were statistically significant varied from 0.001 to 0.470. Despite such a large range of level of significance, it was assumed that the segmented model was the best representation of the high variability among the values in some data sets, particularly considering that 56 percent of the "F" ratios were within the 0.30 level of probability.

Figure 2-4 illustrates the distribution of the transition heights over the number of annual rings from the pith. As can be seen, no systematic variation trend was found, indicating that transition age and height are independent. Table 2-5 gives a summary of average transition ages by sample section heights. These averages were 23, 23, 21 and 23 years for sections sampled at breast height, 20 percent, 40 percent of total height and for all sections, respectively.

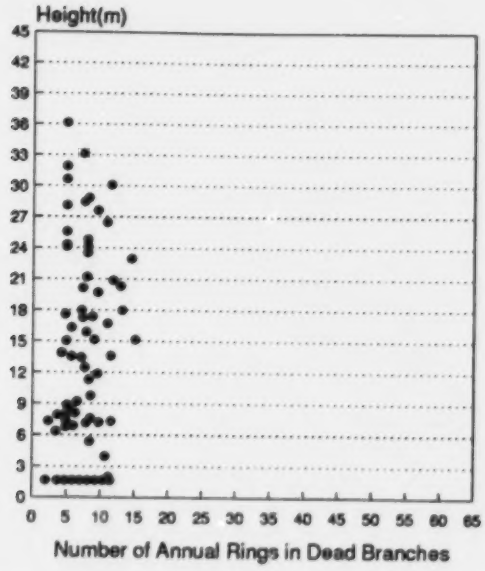


Fig. 2-6 Height in stem versus number of annual rings at the base of dead branches

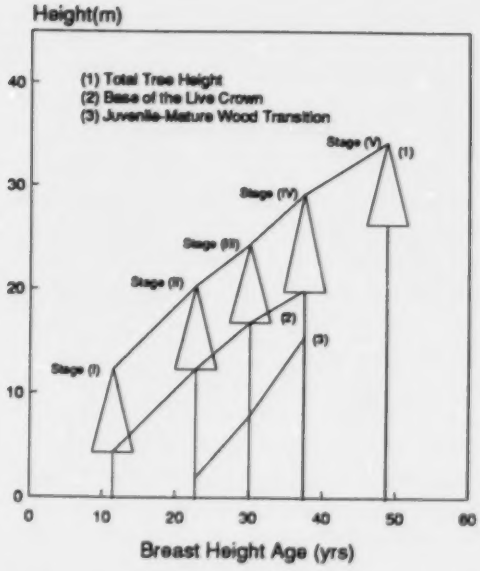


Fig. 2-7 Overall relationship between total tree height, crown base height, and juvenile-mature wood transition height and breast height age

Table 2-6. Summary of the Average Values Found at the Five Stages of Development

	Age (BH) (years)					Juvenile-Mature Wood Transition										Base of the Live Crown					Total Tree Height				
						Age (years)					Height (m)					Height (m)					(m)				
Stage	#Obs.	Mean	s.d.	Max.	Min.	#Obs.	Mean	s.d.	Max.	Min.	#Obs.	Mean	s.d.	Max.	Min.	#Obs.	Mean	s.d.	Max.	Min.	#Obs.	Mean	s.d.	Max.	Min
I	14	12	-	12	12	-	-	-	-	-	-	-	-	-	-	12	4.2	1.28	6.5	2.3	14	11.5	2.19	14.9	7.0
II	14	23	5.77	34	15	14	23	5.77	34	15	14	1.3	-	1.3	1.3	12	11.8	4.07	19.0	6.5	14	20.7	5.82	30.2	9.9
III	14	30	6.69	42	19	14	23	5.72	35	13	14	7.0	1.03	8.5	3.3	12	16.3	3.87	22.0	10.9	14	25.5	5.33	30.5	10.5
IV	9	37	5.89	44	28	9	21	6.05	29	11	9	15.4	1.04	17.2	14.0	9	19.2	4.14	22.7	11.7	9	30.0	4.31	35.0	23.6
V	14	48	9.32	63	33	-	-	-	-	-	-	-	-	-	-	12	21.5	3.15	24.8	15.1	14	34.8	7.01	44.7	18.0

Figure 2-5 illustrates the distribution of the lowest relative density values in each sample section. These values were consistently found within the second to fifteenth annual rings from the pith at any sampling height. The average number of annual rings indicating the lowest relative density was seven, with a standard deviation of 2.9.

Base of the Live Crown

A total of 120 dead branches were sampled from 12 trees in order to approximate the base of the live crown positions before harvest as illustrated in Figure 2-1. Figure 2-6 illustrates the distribution of branches among trees as a function of height position in stem and number of annual rings at the branch base. As can be seen, the general trend was that the number of annual rings found in dead branches increased until reaching a maximum value near the base of the crown at harvest.

As presented in Table 2-1. the overall crown base height at harvest, estimated as the height from the ground to the lowest whorl at which three or more live branches were located, was 19.7 meters, ranging from 9.0 to 24.8 meters and the average crown length was 14.7 meters, ranging from 6.7 to 21.9 meters. The average crown length ratio between crown length and total tree height was 0.42, ranging from 0.34 to 0.61. The overall average crown height, estimated as a function of the average crown radius was 24.2 meters, ranging from 12.0 to 35.0 meters, and the average crown length was 10.2 meters, ranging from 3.9 to 15.1 meters. In some cases this position was also identified as the crown contact or point of intersection with neighboring trees by looking for signs of whipping or breaking damage on the terminal shoots of the branches. The average difference between the positions of the base of the live crown and the average crown height at harvest was 4.2 meters ranging from 0.2 to 10.4 meters.

Table 2-7. Differences Between Height of Juvenile-Mature Wood Transition Point, Height of Crown Base and Total Height

Stage	Height Difference Between Transition Point and Crown Base (m)					Height Difference Between Transition Point and Total Height (m)				
	# Obs.	Mean	s.d.	Max.	Min.	# Obs.	Mean	s.d.	Max.	Min.
II	12	10.2	3.80	17.2	6.0	14	18.9	5.87	28.9	8.6
III	12	8.7	3.40	13.2	2.5	14	18.5	4.32	23.5	7.2
IV	9	3.8	3.28	6.7	-3.1	9	14.5	4.08	22.0	9.7
All Stages	33	7.9	4.31	17.2	-3.1	37	17.7	5.12	28.9	7.2

Relationships Between Juvenile-Mature Wood Transition and Base of the Live Crown

Figure 2-7 illustrates, for 14 trees at five stages of development, the average values of total height, height to crown base and height to juvenile-mature wood transition points as functions of age from the pith at breast height. These values are summarized in Table 2-6. The first four stages of development represent trees before harvest and the fifth stage represents trees at harvest.

The curve representing total tree height (Curve 1) can be classified within Site Classes 35 and 36 for coastal Douglas-fir, according to Bruce (1981).

The curve representing the base of the live crown positions before harvest (Curve 2) is parallel to the total height curve, with a tendency of converging towards the base of the live crown at harvest (Stage V). The degree of certainty in the estimation of the base of the live crown before harvest increases with age. As stated earlier, the decrease in branch vigor followed by a period of senescence might lead to the formation of incomplete or absent annual rings at the branch base. Therefore, the base of the live crown position can be overestimated by counting fewer annual rings, especially at earlier stages of the tree development.

The line joining the points of juvenile-mature wood transition (Line 3) approaches the base of the live crown with increasing age and tree height (Figure 2-7). Table 2-7 shows the differences in average height between the points of juvenile-mature wood transition, base of the live crown and total tree height before harvest.

When testing the project hypothesis before harvest the juvenile-mature wood transition did not occur at the base of the live crown, as previously defined. In Stage I no transition was found, and in Stages II to IV the transition occurred below the base of the live crown. The average height difference between the transition points and the base of the live crown decreased with increasing age and tree height (Figure 2-7 and Table 2-7).

The point of transition could not be determined at harvest age (Stage V) because its definition depends upon the relative density of wood added in later years. Thus, a time gap will be required in order to confirm whether the transition occurs at or below the base of the live crown. However, a possible alternative would be to assume that the crown base and the transition at harvest were comparable to those found at Stage IV in Figure 2-7. The juvenile-mature wood transition at harvest, then, would occur at 3.8 meters below the base of the live crown (Table 2-7).

In order to utilize the juvenile-mature wood estimation in the TASS model, it was assumed that the transition occurred at least 3.8 meters below the base of the live crown. This distance was chosen because it represents the last and most reliable observation (Stage IV). Earlier distances (Stages II and III) were not considered due to the uncertainty in the estimation of the base of the live crown at younger ages. Further validation of the method used to define the base of the live crown at younger ages is recommended.

Open-Grown Trees

A total of 84 relative density profiles (seven trees, 12 sample height positions per tree) were investigated in this section. The trees were analyzed in two groups according to their age class.

The first group comprised trees C01, C02, C03, C06 and C07. For these trees, the average age at breast height was 36 years ranging from 24 to 44 years, the average height was 23.9 meters ranging from 15.2 to 31.8 meters, and the average crown length ratio was 0.94 ranging from 0.87 to 0.97 (Table 2-2). This group of trees was characterized by having fairly constant relative density values from pith to bark and no clear definition of juvenile-mature wood transition zone. The relative density variation patterns, in general, showed a moderate initial decrease from the pith to a point within the fourth to the twenty-fourth annual rings, followed by a gradual increase outwards. Table 2-8a shows a summary of the distribution of these profiles at the different sample heights.

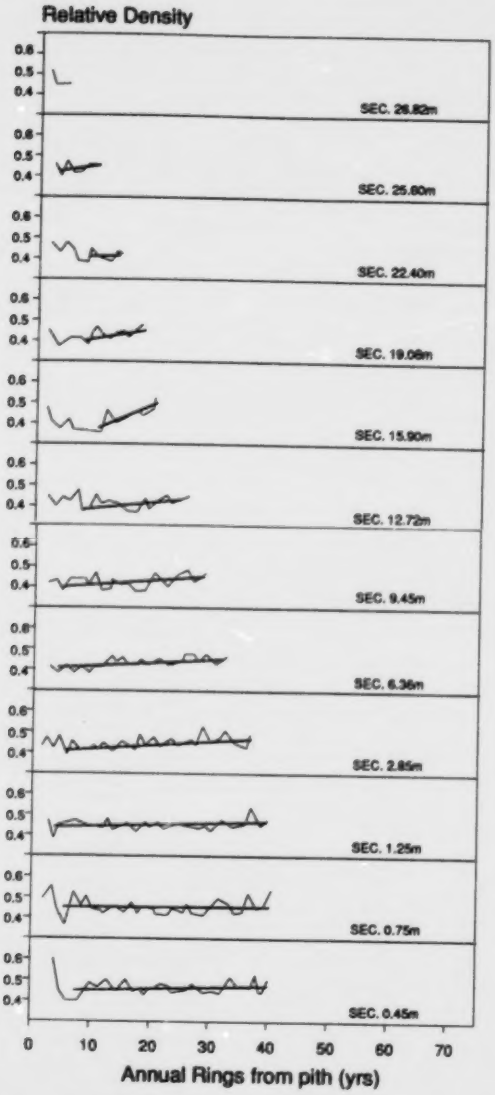


Fig. 2-8 Simple linear regression models fit to pith to bark relative density profiles for tree C02

The overall average number of annual rings was 24, ranging from 3 to 48, and the overall average section height was 9.1 meters ranging from 0.3 to 26.8 meters.

An example of these variation patterns is illustrated in Figure 2-8 for tree C02. As can be seen, simple regression models were fitted to each profile starting from the lowest relative density value outwards, and it was assumed that such profiles represented juvenile wood entirely.

The second group was formed by trees C04 and C05, which had an average age at breast height of 67 years, height of 33.2 meters and crown length ratio of 0.73 (Table 2-2). The distribution of the relative density profiles is presented in Table 2-8b. The overall average number of annual rings was 45, ranging from 7 to 73 and the overall section height was 12.5 meters, ranging from 0.3 to 30.2 meters. The relative density variation patterns of this group showed some evidence of juvenile-mature wood transition zone, particularly in the lower five sample sections.

The relative density profiles of tree C04 showed an initial decrease from the pith to a point within the fourth through twelfth annual rings, followed by a gradual increase and a final decrease outwards. Segmented linear regression models were fitted to the lower five relative density profiles to determine the juvenile-mature transition age (Figure 2-9).

The profiles of tree C05 showed, in general, fairly constant relative density values from pith to bark, without clear definition of a transition zone (Figure 2-10). The profiles from the sections sampled at 0.7 and 3.8 meters from the ground were distinctive in that they indicated some demarcation of a transition zone. Segmented linear regression models were fitted to these profiles which showed an initial relative density decrease in the first annual rings from the pith, followed by a gradual increase over several years and a final leveling off outwards. Table 2-4 gives a summary of the transition ages determined when segmented regression models were utilized. The average transition age for tree C04 was 25 years and for tree C05 was 40 years. Simple linear regression models were fitted to the remaining profiles in both trees and it was assumed that they represented juvenile wood entirely.

As illustrated in Table 2-2 and Table 2-8b, trees C04 and C05 were comparable not only in age, but also in height and crown length ratio at the time of harvest. However, the relative density variation patterns of their lowermost five sample sections were different. This difference can be explained by the fact that tree C04 grew as stand-grown tree until 1953 (age 28 at breast height) when a severe thinning of neighboring trees changed its classification to open-grown. The typical stand-grown relative density variation pattern, and particularly the decrease in density values occurring from the transition point outwards, when the tree was released, supports this interpretation (Figure 2-9).

On the contrary, tree C05 showed only two relative density profiles with juvenile-mature wood transition zone. This inconsistency and the constant relative density values from pith to bark found in the rest of the profiles suggests that this tree, as well as the younger trees described earlier, was open-grown until the time of harvest.

From the above, it is concluded that young and old open-grown trees with a high percentage of the stem covered by live crown, i.e., 76 to 97 percent, will tend to produce primarily juvenile wood, since no clear evidence of juvenile-mature wood transition was generally found.

When relating these findings to the project hypothesis, it was demonstrated that the juvenile-mature wood transition in

Table 2-8. Summary of the Distribution of Relative Density Profiles for Open-Grown Trees

a) Trees CO1, CO2, CO3, CO6 and CO7.

Section Number	Number of Sections	Height (m)				Total Number of Annual Rings			
		Mean	s.d.	Max.	Min.	Mean	s.d.	Max.	Min.
1	5	0.3	0.07	0.4	0.3	40	7.96	48	27
2	5	0.6	0.05	0.7	0.6	38	7.73	47	26
3	5	1.3	0.05	1.3	1.2	36	7.40	44	24
4	5	2.5	0.21	2.8	2.3	34	7.27	39	21
5	5	5.0	0.81	6.3	4.3	28	5.85	32	18
6	5	7.2	1.50	9.4	5.7	24	4.93	28	16
7	5	9.7	2.06	12.7	7.3	21	4.97	25	13
8	5	12.1	2.67	15.9	9.2	18	5.45	22	9
9	5	14.4	3.27	19.0	10.4	15	4.66	18	7
10	5	16.9	3.82	22.4	11.9	12	4.38	16	5
11	5	19.4	4.53	25.6	13.2	9	3.51	12	3
12	4	23.1	2.90	26.8	19.8	5	1.29	7	4
All Sections	59	9.1	7.71	26.8	0.3	24	12.45	48	3

b) Trees CO4 and CO5.

Section Number	Number of Sections	Height (m)				Total Number of Annual Rings			
		Mean	s.d.	Max.	Min.	Mean	s.d.	Max.	Min.
1	2	0.3	-	0.3	0.3	71	3.54	73	68
2	2	0.7	-	0.7	0.7	69	4.24	72	66
3	2	1.3	-	1.3	1.3	67	4.95	70	63
4	2	3.5	0.39	3.8	3.2	62	6.36	66	57
5	2	6.1	0.60	6.5	5.7	55	4.24	58	52
6	2	9.1	1.48	10.2	8.2	51	4.24	54	48
7	2	13.1	0.49	13.5	13.1	45	7.78	50	39
8	2	16.5	0.39	16.8	16.3	37	12.02	45	28
9	2	20.1	0.16	20.2	20.0	31	9.19	37	24
10	2	23.3	0.25	23.5	23.1	24	8.49	30	18
11	2	26.3	0.13	26.4	26.2	15	5.66	19	11
12	2	29.8	0.59	30.2	29.4	8	1.41	9	7
All Sections	24	12.5	10.35	30.2	0.3	45	21.56	73	7

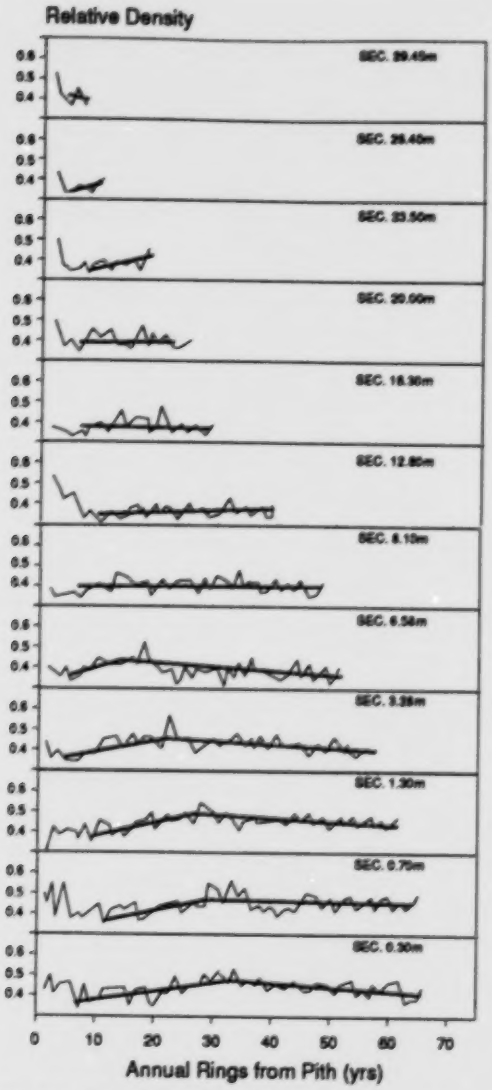


Fig. 2-9 Simple and segmented linear regression models fit to pith to bark relative density profiles for tree C04

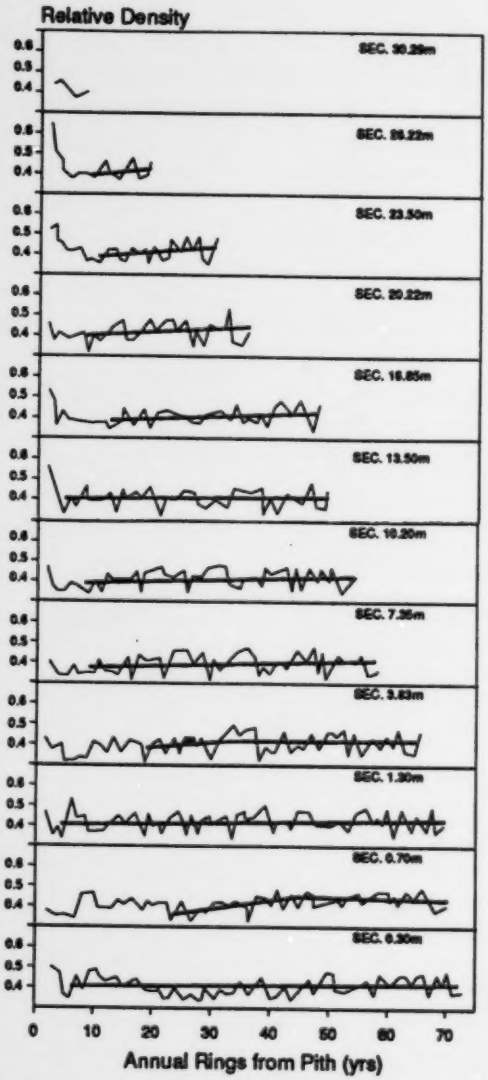


Fig. 2-10 Simple and segmented linear regression models fit to pith to bark relative density profiles for tree C05

open-grown trees did not occur at the base of the live crown position at harvest. Assuming that the transition in stand-grown trees occurs below the base of the live crown we may expect that open-grown trees must have a considerable crown recession in order to allow the occurrence of juvenile-mature wood transition.

Pruned Trees

As was stated in the literature review, the pruning of live and vigorous lower branches in the crown can produce a faster change from juvenile to mature wood, reducing the proportion of juvenile wood core in a given tree. In this project, two pruned trees were analyzed in order to investigate the effects of pruning on relative wood density in relationship to the project hypothesis.

Figures 2-11 and 2-12 show the relative density profiles as a function of number of annual rings from the pith. As shown, additional sample sections at ten percent of total tree height were included because they were located within the pruning area. This area comprised the lower one-third of the live crown, representing a height of approximately four to five meters which was below the sections sampled at 20 percent of total height. In these figures, the arrows in the relative density profiles indicate the year in which the pruning was done, i.e., 1954 or 30 years before the trees were harvested.

The relative density profiles of sections sampled at breast height and 10 percent in tree RF2 showed a gradual initial decrease in the first annual rings from the pith, followed by a sudden increase soon after the pruning, and a final gradual

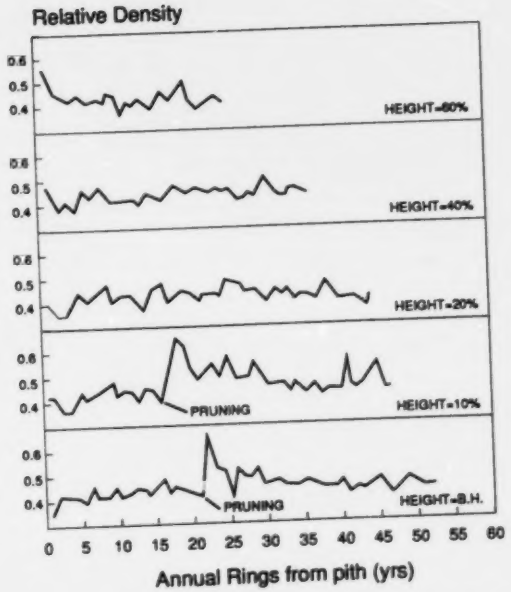


Fig. 2-11 Pith to bark relative density profiles for pruned tree RF2

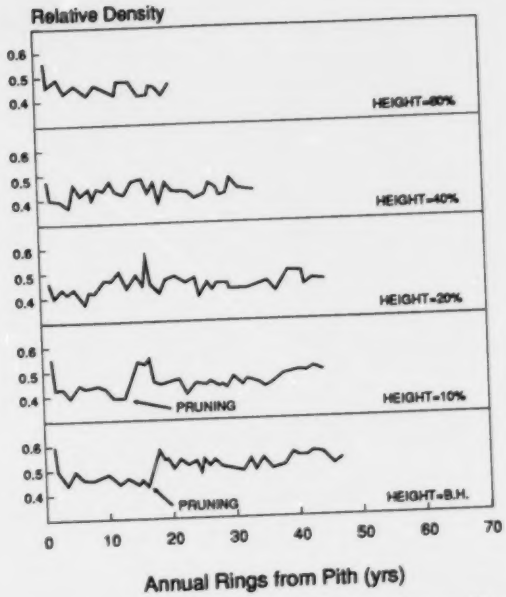


Fig. 2-12 Pith to bark relative density profiles for pruned tree RF3

decrease outwards (Figure 2-11). The profiles for the same sample sections in tree RF3 showed similar variation patterns until after pruning, and then they distinctively showed a final leveling off outwards (Figure 2-12). The different relative density variation patterns of these trees after pruning was probably due to the fact that RF2 was more dominant and open grown than RF3. Therefore, RF2 was able to overcome the effects of pruning in a relatively short time.

The numbers of annual rings from the pith, before pruning, at breast height and 10 percent of total height were 21 and 17 for tree RF2, and 15 and 13 for tree RF3. The overall average number of annual rings of the former sections was 17. This average number also represents an estimate of the juvenile-mature transition occurrence, since it delimits two different relative density variation patterns from the pith.

From the above, it is concluded that the pruning of lower crown live branches can produce both an increase in annual ring mean relative density and a decrease in the proportion of juvenile wood by accelerating the occurrence of juvenile-mature wood transition. Since only two trees were analyzed, these results should be treated as exploratory. However, they are good indicators of possible improvements in wood quality since more high density clear wood can be obtained when pruning is done. Furthermore, assuming that these branches contribute little or nothing to stem wood formation, while utilizing tree resources, it might be worthwhile to consider early pruning of Douglas-fir.

When relating these results to the project hypothesis, it would appear that pruning can accelerate the juvenile-mature wood transition, which otherwise would need more time. Then, if in fact the transition occurs below the base of the live crown in unpruned trees as demonstrated earlier, the transition could be shifted upwards by early pruning of the lower crown live branches.

In view of the above, it is concluded that the juvenile-mature wood transition would occur at the modified base of the live crown, which represents the upper limit of pruning height. Therefore, the hypothesis can be proven as correct. It is important to note that more research on pruned trees is needed for further development of these results.

Conclusions

For the stand-grown trees, the relative density variation patterns at the five sample heights were characterized by an initial decrease to a point within the first annual rings from the pith, followed by a gradual increase and stabilization outwards, particularly in the lower sample sections. No evidence of the juvenile-mature transition zone was found primarily at sections sampled at 60 and 80 percent of total tree height. There is stronger evidence of a transition zone at breast height, and 20 and 40 percent of total tree height. The average juvenile-mature wood transition ages were 23, 23, 21 and 23 years for sections sampled at breast height, 20 and 40 percent

of total height, and for all sections, respectively. Segmented regression analysis, produced a fairly consistent demarcation of the transition zones despite the large variability among the values in some of the relative density profiles. The average crown length ratio for these trees was 0.42. The transition in relative density from juvenile to mature wood, when analyzed before or after harvest, did not occur at the base of the live crown. The last and most reliable transition before harvest occurred 3.8 meters below the base of the live crown. This distance seemed to decrease with increasing age and tree height. This suggests that the transition may approach the base of the live crown as the tree becomes older and taller.

For the open-grown trees, the relative density variation patterns at the twelve sample heights showed an initial decrease from the pith, followed by a gradual increase outwards in the lower sample sections. The relative density values, in general, were fairly constant from pith to bark and without clear evidence of a transition zone. These trees, which were characterized by having a high proportion of the stem covered by the live crown, i.e., 70 to 97 percent, will tend to produce primarily juvenile wood. The relative density transition between juvenile and mature wood did not occur at the base of the live crown. Assuming that the transition occurs below the base of the live crown, open-grown trees must have considerable crown recession in order to show some evidence of transition.

The pruning of lower crown live branches produced both an increase in the annual ring relative density and a decrease in the proportion of juvenile wood by accelerating the juvenile-mature wood transition. When the hypothesis was tested on pruned trees, the transition did occur at the base of the live crown, which represented the upper limit of pruning height. The hypothesis in this case has been proven.

The results of hypothesis testing depended upon the definition given to the base of the live crown, as well as the determination of the transition between juvenile and mature wood. For all the trees analyzed, the size and length of the active live crown seemed to regulate the quantity and quality of juvenile and mature wood in the stem. Further research is needed not only to find a more precise definition of what should biologically be considered the base of the live crown, but also to investigate the implication of such definition on juvenile and mature wood formation.

References

Andrew, S.R. and L.S. Gill. 1939. Determining the time branches on living trees have been dead. J. Forestry 37:930-935.

Barefoot, A.C., R.G. Hitchings, E.L. Elwood and E. Wilson. 1970. The relationship between loblolly pine fiber morphology and kraft paper properties. Tech. Bull. No. 202. N.C. Agric. Exp. St., N.C.S.U., Raleigh. 89p.

Bendtsen, B.A. 1978. Properties of wood from improved and intensively managed trees. For. Prod. J. 28(10):61-72.

Bendtsen, B.A. and J. Senft. 1986. Mechanical and anatomical properties in individual growth rings of plantation-grown eastern cottonwood and loblolly pine. Wood and Fiber Sci. 18(1):23-38.

Briggs, D.G. and W.R. Smith. 1986. Effects of silvicultural practices on wood properties of conifers - a review. In: Douglas-fir: Stand Management for the Future. C.D. Oliver, D.P. Hanley and J.A. Johnson, eds. Univ. of Washington, Institute of Forest Resources Contribution No. 55. Seattle. p.108-117.

Bruce, D. 1981. Consistent height-growth and growth rate estimates for remeasured plots. Forest Sci. 27(4):711-725.

Brunden, M.N. 1964. Specific gravity and fiber length in crown-formed wood. For. Prod. J. 14(1):13-17.

Cooper, G.A. 1960. Specific gravity of red pine as related to stem and crown-formed wood. Iowa State J. Sci. 34(4):693-708.

Cown, D.J. 1973. Effect of severe thinning and pruning treatments on the intrinsic wood properties of young radiata pine. N.Z. J. For. Sci. 3(3):379-389.

Draper, N.R. and H. Smith. 1981. Applied Regression Analysis. 2nd ed. John Wiley and Sons, New York. p.250-254.

Di Lucca, C.M. 1987. Juvenile -mature wood transition in second-growth coastal Douglas-fir. Faculty of Forestry, University of British Columbia, Vancouver, BC. Unpub. M. Sc. Thesis. 162 p.

Forward, D.F. and N.J. Nolan. 1964. Growth and morphogenesis in the Canadian forest species. VII. Progress and control of longitudinal growth of branches in *Pinus resinosa* Ait. Can. J. Bot. 42:923-950.

Fraser, D.A. 1962. Apical and radial growth of white spruce (*Picea glauca* (Moench) Voss) at Chalk River, Ontario, Canada. Can. J. Bot. 40:659-668.

Gerischer, G.F. and A.M. De Villiers. 1963. The effect of heavy pruning on timber properties. For. South Africa. 3:15-41.

Gonzalez, J.S. and R.M. Kellogg. 1978. Evaluating wood specific gravity in a tree improvement program. W.F.P.L. Info. Rep. VP-X.183. Vancouver, BC. 14p.

Hinkley, D.V. 1969. Inference about the intersection in two-phase regression. Biometrika. 56:495-504.

Hudson, D.J. 1966. Fitting segmented curves whose join points have to be estimated. J. Am. Stat. Assoc. 61(316):1097-1129.

Kellogg, R.M. 1982. Coming to grips with wood quality. Forestry Chron. 58(6):254-257.

Larson, P.R. 1963. Microscopic wood characteristics and their variations with tree growth. Presentation to the Working Group on Wood Quality. IUFRO. Madison, WI. 20p.

Larson, P.R. 1965. Stem form of young *Larix* as influenced by wind and pruning. Forest Sci. 11(4):412-424.

Larson, P.R. 1969. Wood formation and the concept of wood quality. Bull. No. 74. Yale Univ. Sch. For. New Haven, CT. 54p.

Larson, P.R. 1973. The physiological basis for wood specific gravity in conifers. In: Proc. Div. 5. IUFRO, Vol. 2, Stellenbosch, South Africa. p.672-680.

Marts, R.W. 1949. Effect of crown reduction on taper and density in longleaf pine. South Lumberman 179:206-209.

Megraw, R.A. 1985. Wood Quality Factors in Loblolly Pine. TAPPI Press. Atlanta, Ga. 88p.

Mitchell, K.J. 1975. Dynamics and simulated yield of Douglas-fir. Forest Sci. Mono. 17. 39p.

Mitchell, K.J. and I.R. Cameron. 1985. Managed stand yield tables for coastal Douglas-fir: Initial density and precommercial thinning. Ministry of Forests, Research Branch. Land Management Rep. No. 31. Victoria, BC. 69p.

Moody, R.C. 1970. Tensile strength of finger joints in pith-associated and non-pith-associated southern pine 2 by 6's. Res. Pap. FPL. 138. USDA For. Ser. For. Prod. Lab., Madison, WI. 20p.

Oliver, C.D. 1986. Silviculture and juvenile wood. In: A Technical Workshop: Juvenile Wood-What Does it Mean to Forest Management and Forest Products? Proceeding 47309 - Forest Products Research Society. Madison, WI. p.29-34.

Panshin, A.J. and C. de Zeeuw. 1980. Textbook of Wood Technology. 4th ed. McGraw-Hill, NY. p.201-240.

Parker, M.L. and L.A. Jozsa. 1973. X-ray scanning machine for tree-ring and density analysis. Wood and Fiber 5(3):192-197.

Parker, M.L., J. Schoorlemmer and L.J. Carver. 1973. A computerized scanning densitometer for automatic recording of tree-ring width and density data from x-ray negatives. Wood and Fiber 5(3):237-248.

Paul, B.H. 1960. The juvenile core in conifers. Tappi 43(1):1-2.

Pearson, E.S. and H.O. Hartley. 1954. Biometrika. Tables for Statisticians. Vol. 1. New York: Cambridge University Press, p.290-299.

Perry, T.O. and C.W. Wang. 1958. Variation in the specific gravity of slash pinewood and its genetic and silvicultural implications. Tappi 41(4):178-180.

Plumptre, R.A. and S. Austin. 1978. The influence of pruning on the density and rate of growth of *Pinus patula*. In: Proc. IUFRO Symposium: Wood Quality and the Utilization of Tropical Species. F.W. Tamolang, ed. FORPRIDECOM, College, Laguna. p.351-370.

Polge, H., R. Keller, and F. Thiercelin. 1973. Influence de l'elagage de branches vivantes sur la structure des acroissements annuels et sur quelques characteristiques du bois de douglas et de grandis. Ann. Sci. For. 30:127-140.

Reeb, D. 1984. Influence of spacing and artificial pruning on the production of clearwood of Douglas-fir. Faculty of Forestry, University of British Columbia, Vancouver, BC. Unpub. M.F. Thesis. 255p.

Rendle, B.J. 1958. A note on juvenile and adult wood. IAWA News Bull. 2:1-6.

Rendle, B.J. 1959. Fast-grown coniferous timber - some anatomical considerations. Quart. J. Forestry 53:116-122.

Rendle, B. J. 1960. Juvenile and adult wood. J. Inst. of Wood Sci. 5:58-61.

Reukema, D.L. 1959. Missing annual rings in branches of young growth Douglas-fir. Ecol. 40:480-482.

Reukema, D.L. 1961. Crown development and its effect on stem growth of six Douglas-fir. J. Forestry 59(5):370-371.

Smith, D.M. 1968. Wood quality of loblolly pine after thinning. Res. Pap. FPL 89. USDA Forest Prod. Lab. Madison, WI. 10p.

Trendelenberg, R. 1935. Variations in the density of important coniferous timbers due to locality, habitat, and difference in individual trees. Imp. For. Inst. Oxford Univ. Translation No. 1. 8p.

Wareing, P.F. 1958. The physiology of cambial activity. J. Inst. Wood Sci. 1:34-42.

Zobel, B.J. 1984. The changing quality of the world wood supply. Wood Sci. Technol. 18:1-17.

Zobel, B.J, C. Webb, and F. Henson. 1959. Core or juvenile wood of loblolly and slash pine trees. Tappi 42(5):345-356.

CHAPTER 3

Longitudinal Shrinkage

J.R. Nault *Wood Science Department, Forintek Canada Corp.*

Introduction

High longitudinal shrinkage has been associated with juvenile wood and rapid-growth for many years. Paul (1938) reported that most of the high longitudinal shrinkage in slash pine took place in wood which contained less than three to four rings per radial inch. He also reached the conclusion that this high shrinkage was caused by the orientation of the fibril elements that make up the fiber walls in the wood. He found that warp accompanying high longitudinal shrinkage could be reduced by drying the wood under restraint, but suggested that the real solution must be that of closely stocking stands to limit growth rates, followed by thinning at appropriate intervals.

Dadswell (1958) reported that longitudinal shrinkage and fibril angle decreased from pith to bark, while tangential shrinkage and fiber length increased. The Forest Products Lab, Madison (1960) found that longitudinal shrinkage from green to oven-dry condition in all species of wood was normally in the 0.1 to 0.3 percent range, although up to 5.8 percent shrinkage had been observed in tests. They reported that with increasing fibril angle longitudinal shrinkage increased, and transverse shrinkage decreased. High longitudinal shrinkage was found to be a problem in compression wood, tension wood and wood of lower than average density for a species. They also found that longitudinal shrinkage was greater in springwood than in summerwood, and greater in fast-growing conifers than in slow-growing ones.

Harris and Meylan (1965), Meylan (1968) and Voorhies (1971) all found that longitudinal shrinkage increased with increasing microfibril angle. Sadoh and Christensen (1967) suggested a method for measuring longitudinal shrinkage in thin sections of wood, and Sadoh and Kingston (1967) applied this method of shrinkage measurement to correlate longitudinal shrinkage and wood structure. Hann (1969), and Voohries and Blake (1981) reported that the extent of longitudinal shrinkage correlated well with distance from pith.

Pearson and Gilmore (1971) found that juvenile wood in loblolly pine (*Pinus taeda* L.) had lower specific gravity than mature wood. They also noted that longitudinal shrinkage decreased with height in the stem, although they found no difference between longitudinal shrinkage in juvenile and mature wood. They attributed this to inadequate sampling of the juvenile wood.

Voorhies and Groman (1982) found that longitudinal shrinkage of ponderosa pine followed a curvilinear pattern, decreasing with each annual increment from the pith to about 20 to 25 rings, and then remaining constant. They also found good correlation between longitudinal shrinkage and fibril angle, and found that fibril angle correlated well with rings from pith.

Bendtsen (1978) presented a limited review of the literature concerning wood properties of improved and intensively managed trees, and concluded that differences in wood properties in these trees as compared to "natural" trees was due to the increased proportion of juvenile wood present.

We may infer that longitudinal shrinkage is a good indicator of microfibril angle, and that by measuring longitudinal shrinkage we may make inferences about the microfibril angle of the wood, and thereby predict associated properties. Longitudinal shrinkage is also a direct indicator of warping through differential shrinkage, another problem in lumber containing juvenile wood.

The objective of this study is to evaluate the extent of juvenile wood in fast-growing stands of coastal Douglas-fir, in terms of longitudinal shrinkage as an indicator of fibril angle.

Materials and Methods

As shown in Figure 3-1, a 12 inch bolt was cut at approximately breast-height from each of the 60 sample trees felled. The bolt was wrapped in plastic to maintain moisture content, transported to Forintek and then frozen as soon as possible. The bolt was cut square to the pith, then parallel to the grain to give a tree diameter sample about 2 inches thick and 10 inches along the grain. This diameter was then planed to a thickness of 1.25 inches, ensuring that the pith was in the center of the sample. The sample was then cut along the pith to give two radial cross-sections, which were then cut square to the pith to give two sections 8 inches along the grain.

The pieces were then sawn on a bandsaw. First, two radial cuts were made to a depth of 7 inches to give three 3/8 inch thick radially oriented boards held together by a 1 inch block at their base. Each of these were then sawn through their thickness at 1/4 inch intervals to give three rows of 1/4 inch x

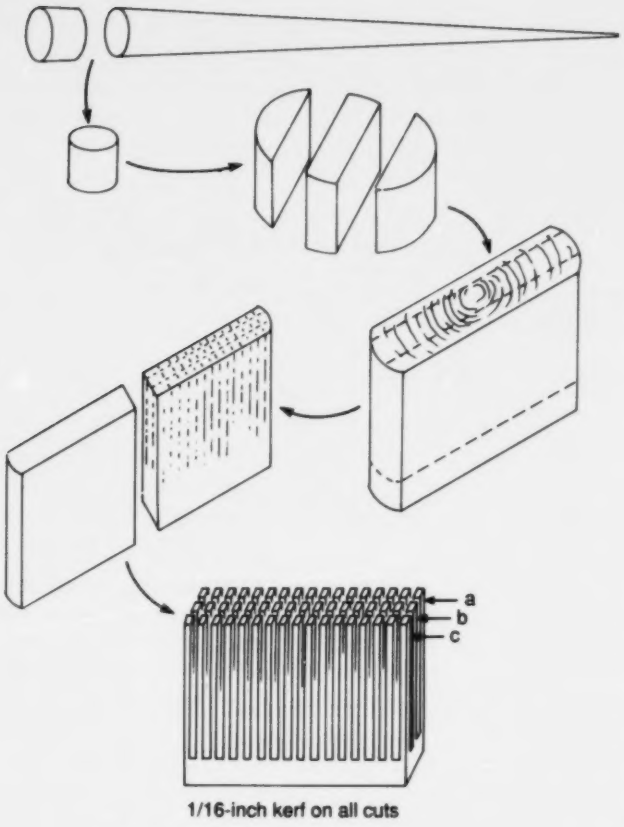


Fig. 3-1 Longitudinal shrinkage sample preparation

3/8 inch prongs joined to a solid base 1 inch thick. This procedure followed a method similar to that of Voorhies and Blake (1981).

Each prong of each radial section was marked in the center, both on the top of the prong and on the base of the block. The blocks were then submerged in water overnight to ensure saturation. A digital caliper was interfaced to a computer for automated data gathering. Each prong was measured to an accuracy of +/-.0005 inch. Following wet measurements, the blocks were oven-dried at 110°C for 48 hours, then each prong was measured again. Longitudinal shrinkage is expressed as a percent length loss based on green length as:

$$\text{Long. Shrinkage} = \frac{\text{(Original Green Length - Oven-Dry Length)}}{\text{(Original Green Length)}} \times 100\%$$

Thus, longitudinal shrinkage was measured for two radii at breast-height from each tree, and each radius was sampled in triplicate (a, b, c on Figure 3-1).

Total stem volume and stem volume with longitudinal shrinkage greater than 0.2 percent was calculated for each tree using data from Forintek's Tree Ring Input Program. This enabled a comparison of the relative amounts of juvenile wood in each tree.

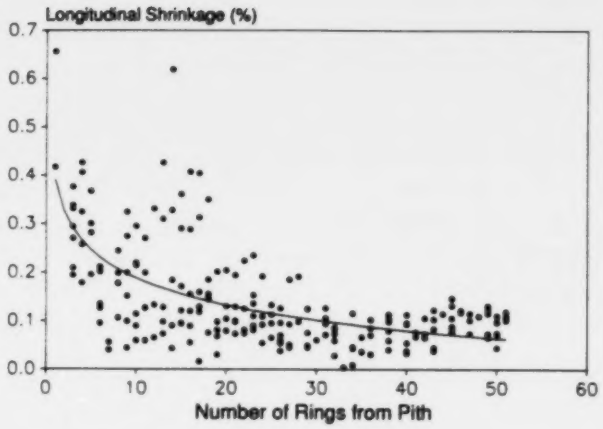


Fig. 3-2 Longitudinal shrinkage versus rings from pith and the fitted model for a single tree

Results and Discussion

Longitudinal shrinkage from green to oven-dry conditions for mature wood of all species is usually in the range of 0.1 to 0.2 percent, although a number of wood quality factors can cause much greater shrinkages. Longitudinal shrinkage is typically higher in the juvenile wood of a tree and decreases until maturity is reached. Since the primary goal of this study was to assess the extent of juvenile wood present in the trees studied, comments here are restricted to juvenile and mature wood differences.

It was difficult to prepare samples which were free of other factors responsible for high longitudinal shrinkage, such as knots and compression wood. It is, thus, difficult to select "typical" data for comparisons. The degree of scatter on the shrinkage plots gives an indication of the irregular behavior of the wood, although many of the exceptionally high longitudinal shrinkage values can be accounted for by the presence of factors such as knots and compression wood.

In order to facilitate comparisons of tree to tree differences, a mathematical treatment of the data was adopted following the model of Voorhies and Groman (1982), in which longitudinal shrinkage is related to number of rings from pith by the formula:

$$\% \text{ Longitudinal Shrinkage} = C \times (\text{Rings from Pith})^{D}$$

From this model linear regression lines were calculated for each tree and each site using the formula:

$$\text{Ln (Longitudinal Shrinkage + 1)} = A + B \times \text{Ln (Rings From Pith)}$$

to prevent calculating logarithms of negative and zero values, 1 was added to each shrinkage value to prevent negative and zero values. Results from the regression analysis are given in Table 3-1. From the regression formula obtained, values for theoretical longitudinal shrinkage based on rings from pith

Table 3-1. Statistical Analysis of Data
Model: LN (Long. Shrink. + 1) = A + B x LN (Rings From Pith)

Site	Tree No.	A	B	Correlation Coefficient
Ladysmith	1	-.007	.0249	.355
	2	.356	-.0601	-.405
	3	.149	-.0132	-.210
	4	.331	-.0689	-.630
	5	.272	-.0447	-.500
	6	.133	.0164	.094
	7	.185	-.0369	-.480
	8	.092	-.0070	-.077
	9	.198	-.0288	-.399
	10	.543	-.117	-.497
	11	.050	.0037	.044
Cassidy	1	.050	.0003	.084
	2	.051	.0003	.049
	3	.457	-.114	-.614
	4	.083	-.0028	-.024
	5	.248	-.0507	-.611
	6	.163	-.0174	-.120
	7	-.030	.0185	.230
	8	.060	-.0066	-.096
	9	.122	-.0126	-.075
	10	.359	-.0520	-.243
Campbell River	1	.103	-.0106	-.227
	2	.173	-.0280	-.454
	3	.298	-.0505	-.443
	4	.146	-.0296	-.408
	5	.471	-.0946	-.515
	6	.263	-.0540	-.543
	7	.210	-.0223	-.216
	8	.252	-.0572	-.557
	9	.087	.0122	.135
	10	.349	-.0580	-.497
Cowichan Lake	1	.142	-.0080	-.076
	2	.040	.0108	.131
	3	.381	-.0904	-.566
	4	.248	-.0529	-.465
	5	.337	-.0940	-.648
	6	.432	-.117	-.649
	7	.200	-.0421	-.415
	8	.208	-.0506	-.442
	9	.309	-.0724	-.557
	10	.310	-.0859	-.490
Lizard Lake	1	.156	-.0062	-.051
	2	.264	-.0478	-.441
	3	.172	-.0309	-.459
	4	.177	-.0364	-.397
	5	.119	-.0054	-.103
	6	.015	.0573	.457
	7	.226	-.0324	-.348
	8	.225	-.0259	-.248
	9	.149	-.0189	-.252
	10	.069	.0036	.046
Jordan River	1	.438	-.0698	-.464
	2	.222	-.0312	-.343
	3	.206	-.0334	-.417
	4	.253	-.0250	-.217
	5	.142	-.0070	-.047
	6	.159	-.0218	-.415
	7	.496	-.136	-.814
	8	.133	-.0174	-.252
	9	.327	-.0666	-.496
	10	.269	-.0506	-.456

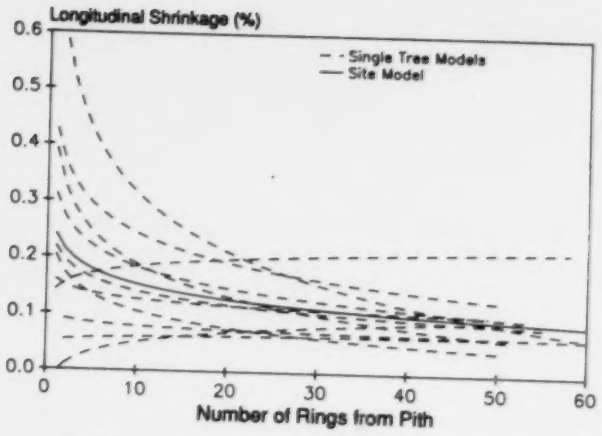


Fig. 3-3 Models for longitudinal shrinkage versus rings from pith for one site

were determined and plotted for each tree. Figure 3-2 illustrates the data from one tree and the model fit to this data. Note the large degree of scatter in the data.

Almost all trees followed the pattern of higher longitudinal shrinkage near the pith, with a rapid decrease to lower levels. There were large tree to tree differences in the extent of wood with high longitudinal shrinkage and the magnitude of this shrinkage. Of the trees not following this pattern, most can be accounted for by the presence of compression wood and knots in the sampled radii. Figure 3-3 shows the models for 10 trees from one site and the model attained when the data from these 10 trees is pooled.

The degree of fit varied from tree to tree depending on the degree of scatter in the data and the amount of unusual wood present. However, these lines are useful in illustrating the large tree to tree variation, providing undue emphasis is not placed on small differences.

For each tree, juvenile wood was arbitrarily defined as the wood extending from the pith to the point where longitudinal shrinkage in the model decreased to 0.2 percent. The juvenile wood was thus taken to be from 0 to 40 rings from the pith with the average being 5 rings. Using calculated stem volumes from the TRIP program, the juvenile wood is thus considered as representing from 0 to 54 percent of total stem volume with the average being 2.3 percent. (Based on shrinkage measurements at breast height only.)

When the data from all trees was pooled, longitudinal shrinkage in the model remained low across the radius, with the calculated values never exceeding 0.3 percent (Figure 3-4).

Figure 3-5 presents the arithmetic mean longitudinal shrinkage over all samples studied and the 90% confidence interval for the mean, on a ring by ring basis. Note the close agreement between the modelled shrinkage and the mean, and the wide confidence interval. The width of the confidence interval is an indicator of how much variation was present from tree to tree

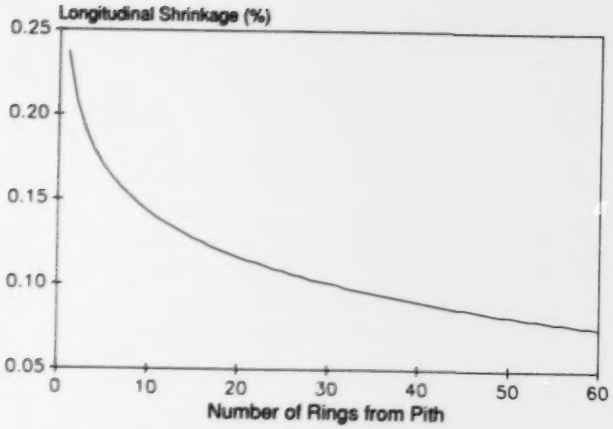


Fig. 3-4 Model for longitudinal shrinkage versus rings from pith for all trees

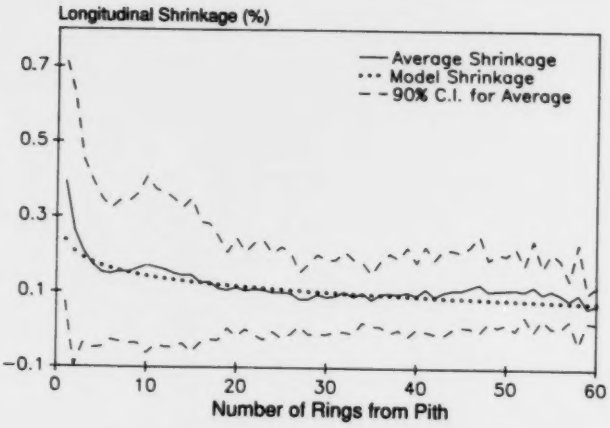


Fig. 3-5 Longitudinal shrinkage summary for all trees

and radius to radius for each ring. The mean shrinkage decreases to below 0.20% by the fourth ring, as opposed to five rings when individual tree models are used, and three rings when the model from all data is used.

If the breakpoint method as described by DiLucca in Chapter 2 is applied to the mean shrinkage values, juvenile wood is defined as 3.5 rings, which is essentially the same as the previous values mentioned. A slightly modified breakpoint method where the shrinkage in mature wood is considered constant (Cook and Barbour, 1988) defines juvenile wood as 4.6 rings, again close to the previous values.

Conclusion

On the basis of these longitudinal shrinkage observations from an extensive sampling of second-growth coastal Douglas-fir no sharp distinction can be made between juvenile and mature wood. Although shrinkage values are generally high near the pith and decline with increasing rings from pith the changes between the two types of wood are gradual, so any distinction made between them is arbitrary. One could obtain different amounts of juvenile wood in any given tree depending upon which shrinkage criteria were used to define it. Based on the longitudinal shrinkage criteria of 0.2 percent, the estimate of the number of rings from the pith to the juvenile-mature wood boundary is substantially lower than estimated by the pattern of relative density change. It would appear that the volume of wood adversely affected by high longitudinal shrinkage is considerably less than that affected by low relative density.

Although on average only a small percentage of stem volume was found to exceed 0.2 percent shrinkage, it must be remembered that including this wood in the same piece of lumber with wood having lower levels of shrinkage will result in warp. As well, a very large tree to tree variation in longitudinal shrinkage was observed. Thus, some trees had an appreciable fraction of stem volume with high shrinkage, and lumber produced from these trees could present an unacceptable level of degrade. It should be pointed out that since all longitudinal shrinkage values were based on drying the wood to the oven-dry condition, shrinkage in kiln-dried lumber would be less, due to the higher moisture content.

References

Forest Products Lab, Madison, Wisc. 1960. Longitudinal shrinkage of wood. Report No. 1093 U.S. Forest Serv. FPL, Madison, WI. 10p.

Bendtsen, A.B. 1978. Properties of wood from improved and intensively managed trees. For. Prod. J. 28(10):61-72.

Cook, J.A. and R.J. Barbour. 1988. The use of segmented regression analysis in the determination of juvenile and mature wood properties. Forintek Canada Corp., Vancouver, BC. Unpublished internal report. 20p.

Dadswell, H.E. 1958. Wood structure variations occurring during tree growth and their influence on properties. J. Inst. Wood Sci. 1(1)11-33.

Hann, R.A. 1969. Longitudinal shrinkage in seven species of wood. U.S. Forest Serv. Res. Note. FPL-0203. FPL, Madison, WI. 12p.

Harris, J.M. and B.A. Meylan. 1965. The influence of microfibril angle on longitudinal and tangential shrinkage in *Pinus radiata*. Holzforsch. 19(5):144-153.

Meylan, B.A. 1968. Cause of high longitudinal shrinkage in wood. For. Prod. J. 18(4):75-78.

Paul, B.H. 1938. Reducing bowing and crooking of lumber cut from second growth southern yellow pine. Southern Lumberman. Jan. 1, 1938. 2p.

Pearson, R.G. and R.C. Gilmore. 1971. Characterization of the strength of juvenile wood of loblolly pine (*Pinus taeda* L.). For. Prod. J. 21(1):23-31.

Sadoh, T. and G.N. Christensen. 1967. Longitudinal shrinkage of wood. Part I: Longitudinal shrinkage of thin sections. Wood Sci. Tech. 1(1):26-44.

Sadoh, T. and R.S.T. Kingston. 1967. Longitudinal shrinkage of wood Part II: The relation between longitudinal shrinkage and structure. Wood Sci. Tech. 1(2):81-98.

Voorhies, G. 1971. The cause of warp in young-growth ponderosa pine lumber. For. Note. No. 6. Northern Ariz. Univ., Flagstaff, AZ. 7p.

Voorhies, G. and B.R. Blake. 1981. Properties affecting drying characteristics of young-growth ponderosa pine. For. Note. No. 14. Northern Ariz. Univ., Flagstaff, AZ. 27p.

Voorhies, G. and W.A. Groman. 1982. Longitudinal shrinkage and occurrence of various fibril angles in juvenile wood of young-growth ponderosa pine. For. Note. No. 16. Northern Ariz. Univ., Flagstaff, AZ. 25p.

CHAPTER 4

Fiber Length

E.A. Hamm *Wood Science Department, Forintek Canada Corp.*

Introduction

Fiber length is an anatomical property which has been found to be related to the paper making properties of pulp (Britt, 1970, Haygreen and Bowyer, 1982). Although there has been no direct evidence that fiber length is related to solid wood product properties, there have been some studies which suggest either a direct or indirect relationship between fiber length and certain mechanical properties of small clearwood specimens. For example, Wardrop (1951) found that the tensile strength of radiata pine and Douglas fir was positively related to fiber length. Fibril angle has been found to be highly correlated to strength of microsamples (Mark, 1967) and fiber length in turn has been related to fibril angle. Gray and Kyanka (1974) explained the increase in modulus of elasticity in bending of small clear specimens of fertilized versus unfertilized red pine on the basis of the increasing number of thick-walled earlywood cells for the fertilized material combined with an overall decrease in fiber length. No rationale for the length effect was presented, although circumstantial evidence would suggest an inverse relationship between cell wall thickness and length. Bendtsen and Senft (1986) obtained a positive correlation between fiber length and mechanical properties in bending tests of small loblolly pine specimens. Coefficients of correlation were as high as 0.79.

Juvenile wood possesses anatomical properties different from those of mature wood (Haygreen and Bowyer, 1982). With increased harvesting of younger managed stands, it is important to determine what changes in anatomical properties will occur in our wood resources as a result of the shift to younger growth forest stands (Kellogg, 1982). The objective of this study was to determine the distribution of fiber length in stemwood of second-growth coastal Douglas-fir trees and examine the implications of harvesting second growth timber relative to changes in this property.

Methods and Materials

The sampling procedure used to obtain material for fiber length analysis is shown in Figure 1-2. Three trees per site and 5 height positions per tree were sampled. These were the same three trees selected by Paprican for the pulp property studies. At all height positions a mean fiber length for each 5 year growth increment was obtained up to age 20, and for each 10 year increment thereafter.

The material for each of these samples was prepared for fiber length measurement by first splitting it into 5 millimeter thick segments. Pulping of these segments was then carried out in Paprican's minidigester (Keays and Bagley, 1970) which contained up to 16 one liter stainless steel cylindrical bombs. Approximately 5 samples, separated by stainless steel screens were placed in each bomb. A measured amount of cooking liquor with 16 percent effective alkali was added to obtain a 5-6:1 liquor to wood ratio based on oven-dry weight of wood. Maximum cooking temperature was 170°C and cooking time varied from 85 to 105 minutes. After cooking the chips were disintegrated in a blender, washed in cold water to remove the remaining liquor, and screened on a 200 mesh vibrating flat screen to remove shives.

A slurry of approximately 1000:1 by weight was prepared for the Kajaani FS-100 Optical Fiber Length Analyzer, on which the measurements were done, and a minimum of 2000 fibers as recommended by Kajaani was analyzed for each sample. A built-in microprocessor along with a printer and plotter connected to the fiber length analyzer produced a printout of the number of fibers in 0.2 millimeter categories and a plot of the frequency distributions in either arithmetic or weighted length form. Arithmetic and weighted mean fiber lengths were calculated as follows:

$$\bar{l}_a = \sum_{i=1}^{n} l_i n_i \Big/ \sum_{i=1}^{n} n_i$$

$$\bar{l}_w = \sum_{i=1}^{n} l_i^2 n_i \Big/ \sum_{i=1}^{n} l_i n_i$$

where l_i = length of the ith length category and n_i = number of fibers in the ith category. A personal computer was interfaced with the fiber length analyzer to store the data for further processing. Due to the presence of cut and broken fibers and the inability of the Kajaani to separate cut fibers from whole, arithmetic length frequency distributions tended to be binodal in nature, as illustrated in Figure 4-1. When the lengths were weighted, the first peak of the arithmetic distribution disappeared and the distribution curve became

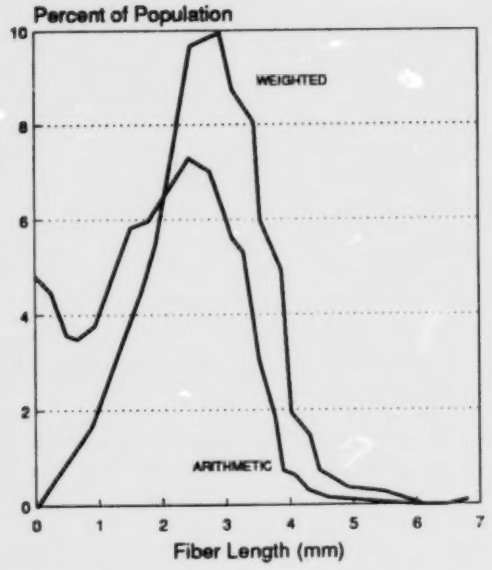


Fig. 4-1 Arithmetic and weighted fiber length distributions for breast height material, age 6-10 years, from tree F6

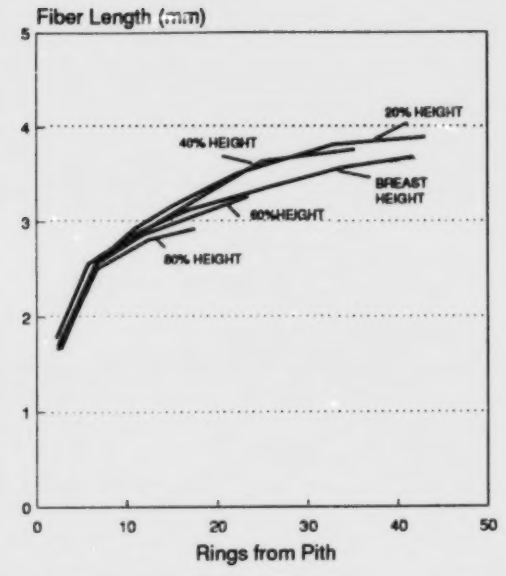


Fig. 4-2 Weighted average fiber length versus rings from pith by sampling height

Table 4-1. Arithmetic and Weighted Mean Fiber Length (mm) for Each Age Increment at Various Height Positions

Age		0 - 5		6 - 10		11 - 15		16 - 20		21 - 30		31 - 40		41 - 50	
Height		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
BH	Arith.	1.31	0.15	1.92	0.15	2.15	0.21	2.32	0.22	2.50	0.21	2.63	0.28	2.63	0.36
	Wtd.	1.66	0.16	2.39	0.16	2.66	0.21	2.89	0.21	3.12	0.19	3.31	0.30	3.285	0.33
20%	Arith.	1.34	0.17	2.01	0.24	2.37	0.20	2.55	0.23	2.76	0.31	3.04	0.45	3.06	0.50
	Wtd.	1.73	0.17	2.50	0.22	2.90	0.22	3.16	0.24	3.46	0.30	3.76	0.44	3.81	0.42
40%	Arith.	1.32	0.17	2.09	0.25	2.35	0.29	2.53	0.28	2.97	0.37	2.91	0.45		
	Wtd.	1.72	0.21	2.60	0.28	2.91	0.34	3.21	0.27	3.65	0.34	3.74	0.34		
60%	Arith.	1.27	0.16	2.04	0.17	2.35	0.23	2.50	0.34	2.77	0.34				
	Wtd.	1.65	0.18	2.53	0.17	2.88	0.18	3.09	0.36	3.38	0.36				
80%	Arith.	1.19	0.12	1.97	0.18	2.19	0.14	2.13	0.12						
	Wtd.	1.57	0.12	2.41	0.20	2.17	0.15	2.91	0.10						

more normally distributed. It was observed from the frequency distribution plots that in some cases after the frequency had dropped to zero at the high end of the length scale additional fibers occurred at higher lengths. It was decided that these observations were due to overlapping of two or more fibers, and therefore were excluded from the calculation of means.

Results and Discussion

A summary of the mean arithmetic and weighted fiber lengths for each age increment across the stem, at the various height positions is given in Table 4-1. Examination of fiber length distribution across the stem revealed that there was a pronounced non-linear increase in fiber length from pith to bark at all height positions. Figure 4-2 shows plots of mean weighted fiber lengths from pith to bark for the five height positions. The following inverse exponential equation with three constants gave the best fit to the fiber length versus age data:

$$l = a - b\,[\exp(-ct)] \qquad (1)$$

where:

l = Fiber length (mm)
t = Cambial age in years
a,b,c = constants

Table 4-2. Coefficients and Confidence Intervals of Fiber Length Versus Age Equation

Height Position	Coefficient a	Confidence Interval (95%)	Coefficient b	Confidence Interval (95%)	Coefficient c	Confidence Interval (95%)
Breast	3.32	3.22 - 3.43	2.08	1.90 - 2.26	0.10	0.08 - 0.12
20%	3.89	3.69 - 4.09	2.57	2.36 - 2.78	0.08	0.06 - 0.09
40%	3.90	3.64 - 4.16	2.65	2.40 - 2.90	0.08	0.06 - 0.11
60%	3.41	3.21 - 3.61	2.39	2.15 - 2.62	0.13	0.09 - 0.16
80%	2.93	2.70 - 3.16	2.17	1.96 - 2.38	0.19	0.11 - 0.26

Table 4-2 contains values and confidence intervals for the three coefficients for each of the five height positions sampled. It would appear from examination of the coefficients that the equations for 20 and 40 percent were identical, equations for breast-height and 60 percent were similar, and the 80 percent height equation was in a class by itself.

The pith to bark trend in fiber length was recognized in the field of wood biology by Sanio as early as 1872 for Scots pine (*Pinus sylvestris*) (Bannan and Bayly, 1956). Numerous other investigators have observed the same phenomenon including Bailey and Faull (1934) in redwood (*Sequoia sempervirens*), Berkley (1934) in southern pines (*Pinus taeda, palustris* and *echinata*), Bisset *et. al* (1951) in radiata and pinaster pine (*Pinus radiata* and *pinaster*), Bannan (1967) in white pine and white spruce (*Pinus monticola* and *Picea glauca*), France and Mexal (1980) in Engelmann spruce and lodgepole pine (*Picea engelmannii* and *Pinus contorta*), and most recently by Megraw (1986) in Douglas-fir (*Pseudotsuga menziesii*). Bannan and Bayly (1956) proposed the following explanation for the observed pattern. An excess number of daughter cells is formed by anticlinal division during the formation of new radial files. Carbohydrates, minerals and moisture are supplied via ray cells to the fusiform initials from which new radial files of tracheids arise, and survival chances for newly formed initials increase with increasing number of ray contacts. Since longer initials have a greater number of ray contacts, a selection in favor of longer cells occurs during peripheral growth of a tree. Cells which do not survive shorten, undergo wall thickening and are added to the mature xylem tissue.

Table 4-3 gives cross-sectional mean fiber lengths and standard deviations at each height position. From Table 4-1 and Figure 4-2, it can be seen that the longest lengths for each age increment were located at the second and third positions i.e., at 20 and 40 percent of the tree height, while the shortest lengths were found at the top position of 80 percent height. The lengths obtained in this study tended to be somewhat shorter than those reported for Douglas-fir by other investigators (Megraw, 1986; Isenberg, 1980). A value of 3.9 millimeters is given by Isenberg as opposed to an overall mean of 3.1 millimeters obtained here for all 17 trees.

Table 4-3. Length Weighted Mean Fiber Length at Each Height Position

No. Trees	Height Position	Mean Fiber Length (mm)	Standard Deviation
16	breast	3.01	0.21
16	20 %	3.25	0.34
16	40 %	3.20	0.27
17	60 %	2.91	0.30
17	80 %	2.46	0.25

A plot of fiber length versus growth rate for the first 5 rings from pith at breast-height (Figure 4-3) indicated no relationship between the two parameters. Correlations with other age increments were not meaningful due to the large variation in fiber length and the narrow range in growth rate. Numerous investigations have been made of correlations between radial growth rate and tracheid length, but overall, no direct causal relationships have been found between the two variables (Richardson, 1964). While interactions between tracheid length and day or night temperatures as well as daylength have been found, it was concluded that the influence of temperature could be direct while that of photoperiod could be both direct and indirect (Richardson, 1964).

Richardson also reported that a high positive correlation between tracheid length and height increment was found in the leaders of Sitka spruce seedlings, although he stated that this trend may not hold in internodes further down the stem from the leader. This correlation was confirmed by Dinwoodie (1963) in 17 year old Sitka spruce.

In addition to the environmental factors discussed above, tracheid length is under a significant degree of genetic control (Zobel and Talbert, 1984) and therefore potential exists for increasing tracheid length through tree breeding. In order to achieve genetic gain a wood characteristic must exhibit tree to

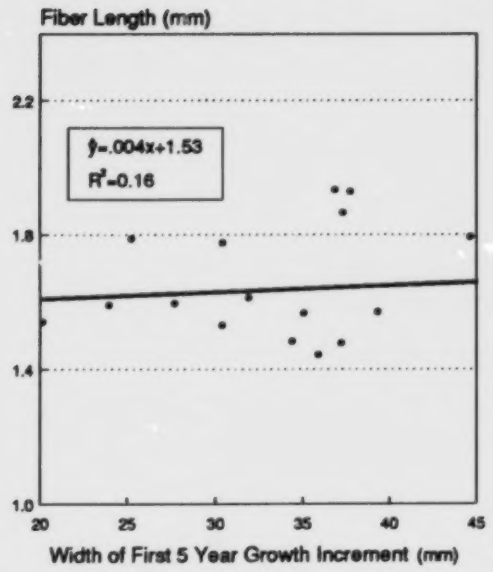


Fig. 4-3 Weighted average fiber length versus growth rate at breast height for first five rings from pith

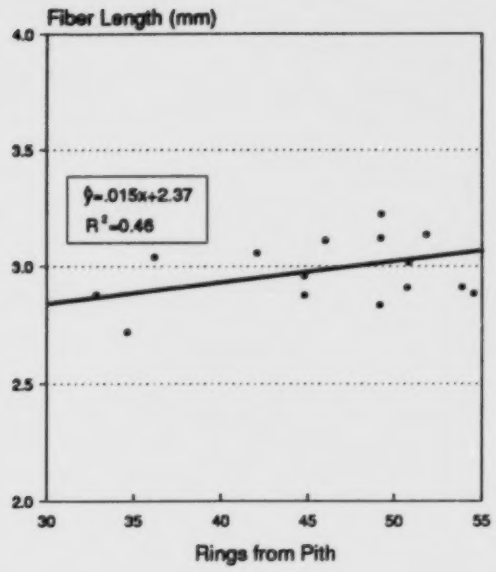


Fig. 4-4 Weighted tree fiber length versus rings from pith at breast height for tree F6

tree variability and it must be heritable. From a practical standpoint of seed orchard development it must also be possible to evaluate the potential or ranking of an individual tree at the expected harvest age based on an early assessment of the characteristic. Unless a wood characteristic can be assessed in a progeny test at about age ten to fifteen there is little chance that the breeder will seriously consider it as a selection criterion. To do this a good correlation must exist between the characteristic, in this case fiber length, at some accessible height position, i.e., breast-height, at this early age versus the average fiber length for the merchantable stem at the expected harvest age. The study of these correlations goes beyond the objectives of this study. However, because the pith to bark fiber length trends are so similar at different height positions, as already observed in Figure 4-2, it strongly suggests that rankings based on the age-age correlation at the convenient breast-height position will adequately reflect the whole tree behavior.

Since fiber length increases with increasing number of rings from pith across the stem it would be expected that mean tree fiber length would increase with age. A slight positive correlation between tracheid length and breast-height tree age can be observed in Figure 4-4, which is a plot of tree fiber length versus rings from pith. If equation (1) is regarded as a function then the method for obtaining the mean of a function can be applied to obtain the mean section fiber length between any two ring ages, t_i and t_{i+1}, as follows:

$$\bar{l} = 1 \Big/ (t_i - t_{i-1}) \int_{t_{i-1}}^{t_i} [\, a - b \cdot \exp(-ct) \,]\, dt \qquad (2)$$

Since the cross-sectional area to which any given age increment applies is not constant, the mean should be weighted by area. If a constant age increment of five years is chosen, then the weighted mean for an area from the pith to any age n would be calculated by the following formula, obtained after integration:

$$\bar{l} = \frac{\sum_{i=1}^{n} A_i / 5\left\{ at_i + (b/c)e^{-ct_i} - \left[at_{i-1} + (b/c)e^{-ct_{i-1}} \right] \right\}}{\sum_{i=1}^{n} A_i} \qquad (3)$$

where A_i is the area of the ith growth increment.

The right hand column in Table 4-4 gives figures for area weighted mean fiber length at different ages for a cross-section of one of the trees studied. For the reasons given previously it was considered that a breast-height cross-sectional area weighted length was an adequate measure of whole stem volume length. The radial growth was extrapolated from the breast-height age of 52 to 100 years. These figures indicate that if a tree was harvested at age 50 instead of 100 a decrease in fiber length of approximately 4 percent would be realized, and at age 40 would result in a 7 percent decrease. This calculation should be done using mean growth rates for a stand since the curve equation (1) is based on was obtained from the mean of 17 trees. These figures do indicate, however that a significant decrease in fiber length will result from a shift to the utilization of second growth stands.

Mean tree fiber lengths (Table 4-5) were calculated by weighting the values at each height position according to the

Table 4-4. Illustration of Procedure for Calculating Area Weighted Mean Fiber Lengths for Tree A-2

Age Increment (years)	Upper Radius (cm)	Incremental Area $(cm)^2$	Cumulative Area $(cm)^2$	Mean Fiber Length (mm)	Cumulative Weighted Mean Fiber Length (mm)
0-5	3.5	38.5	38.5	1.68	1.68
6-10	7.2	124.3	162.8	2.32	2.17
11-15	11.2	231.2	394.0	2.71	2.49
16-20	13.6	187.0	581.0	2.96	2.64
21-30	16.2	243.4	824.4	3.18	2.80
31-40	19.0	309.6	1134.0	3.22	2.91
41-50	22.5	456.3	1590.3	3.30	3.02
51-100	28.0[1]	872.6	2462.8	3.32	3.13

1. Based on extrapolation of radial growth to 100 years

Table 4-5. Length Weighted Mean Fiber Lengths for Each Tree

Tree No.	Age (yrs)	Mean Tree Fiber Length (mm)
A2	52	3.13
A7	50	3.29
A9	55	2.92
B1	50	3.47
B9	59	3.54
B13	56	2.90
C2	53	3.38
C7	45	3.00
D2	37	3.09
D5	33	2.88
D6	35	2.70
E5	47	3.27
E7	43	3.12
E9	50	2.81
F2	52	2.98
F6	45	2.87
F8	57	3.15

volumes occupied by each bole segment. Although mean fiber length increased with age across the stem, the variability also increased dramatically. Figure 4-5 illustrates this by giving weighted distributions for each age increment across the stem at breast-height for one tree. This phenomenon was also observed by Bannan and Bayly (1956) who attributed it to fluctuations in the rate of cambial cell division. When the frequency of cell division is high, a selection in favor of longer cells occurs, as mentioned above. A lower frequency would however, result in a lower survival rate and a greater number of short cells.

If it was considered important to compensate for the reduction in fiber length resulting from a reduction in harvest age, two strategies exist: improvement of the resource through biological means such as breeding programs and/or forest

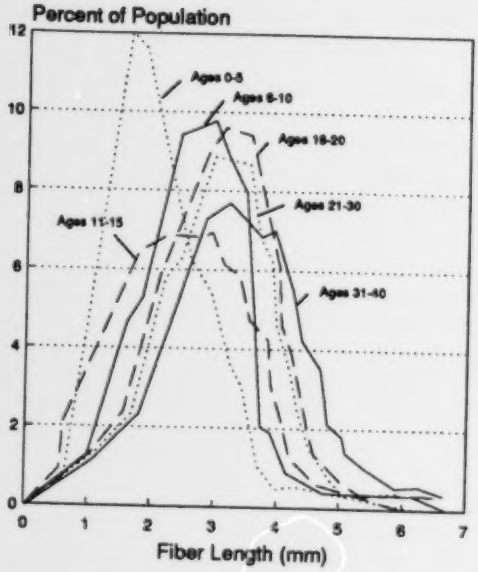


Fig. 4-5 Weighted fiber length distribution by breast height age for tree F6

management techniques, and through technological means by changes in processing technology and methods. The potential of using breeding programs to improve fiber length was mentioned earlier.

Before forest management techniques such as spacing and thinning could be applied to fiber length improvement, the relationship with both leader and radial growth rate of the species in question would have to be known. Richardson (1964) pointed out that radial correlations have been either positive, negative or nonexistent. Megraw (1985) reported that a reduction in radial fiber length resulted from both fertilization and thinning of several species of pines while Richardson (1964) and Dinwoodie (1963), as mentioned above, found a positive correlation with leader growth in Sitka spruce. As has been stated previously, the range in growth rate was too narrow in material used for this study to be able to obtain meaningful correlations with fiber length.

In the field of processing technology, beating of fibers to improve paper properties is well known.

Conclusions

1. Fiber length in the 17 coastal Douglas-fir trees studied increased in an inverse exponential manner with age from pith across the stem, with a fairly steep increase observed in the first 30 years and a leveling-off occurring beyond that. This was in agreement with results obtained by other investigators as early as before the turn of the century. Variability in mean fiber length also increased with age from pith.

2. Longest lengths for all age increments were observed at either the 20 or 40 percent height positions and shortest at the 80 percent position.

3. A decrease in mean fiber length of approximately 4 percent would result from reducing the harvest age from 100 to 50 years, based on extrapolating the fiber length versus age equation from the maximum age of 59 years for trees studied here to 100 years.

Recommendations

A more intensive examination should be made of resource management and processing techniques which could be applied to minimize reduction in product quality due to changes in fiber length. Also further studies should be conducted on the influence of fiber length on solid wood properties.

References

Bailey, I.W. and A.F. Faull. 1934. The cambium and its derivative tissues. No. IX: Structural variability in the Sequoia Sempervirens, and it's significance in the identification of fossil woods. Jour. Arnold Arboretum (Harvard Univ.). 15:233-254.

Bannan, M.W. 1967. Sequential changes in rate of anticlinal division, cambial cell length, and ring width in the growth of coniferous trees. Can. J. Bot. 45:1359-1369.

Bannan, M.W. and I.L. Bayly. 1956. Cell size and survival in conifer cambium. Can. J. Bot. 34:769-776.

Bendtsen, B.A. and J. Senft. 1986. Mechanical and anatomical properties in individual growth rings of plantation-grown eastern cottonwood and loblolly pine. Wood and Fiber Sci. 18(1):23-38.

Berkely, E.E. 1934. Certain physical and structural properties of three species of southern yellow pine correlated with compression strength of their wood. Ann. Missouri Botan. Garden. 21:241-338.

Bisset, I.J.W., H.E. Dadswell and A.B. Wardrop. 1951. Factors influencing tracheid length in conifer stems. Australian Forestry. 15:17-30.

Britt, K.W. 1970. Handbook of Pulp and Paper Technology. Van Nostrand Reinhold, New York. p.360.

Dinwoodie, J.M. 1963. Variation in tracheid length in *Picea sitchensis* (Carr.). Department of Scientific and Industrial Research. Forest Products Research Special Report No. 16. Her Majesty's Stationery Office. London. p.11.

France, R.C. and J.G. Mexal. 1980. Morphological variation of tracheids in the bolewood of mature *Picea engelmanni* and *Pinus contorta*. Can. J. For. Res. 10:573-578.

Gray, R.L. and G.H. Kyanka. 1974. Potassium fertilization effects on the static bending properties of red pine wood. For. Prod. J. 24(9):92-96.

Haygreen, J.G. and J.L. Bowyer. 1982. Forest Products and Wood Science - An Introduction. The Iowa State University Press. Ames, IO. p.278.

Isenberg, I.H. 1980. Pulpwoods of the United States and Canada. Volume I: Conifers. 3rd ed. The Institute of Paper Chemistry, Appleton, WI. p.118-119.

Keays, J.L. and J.M. Bagley. 1970. Digester assembly for precision pulping studies. Tappi. 53(10):1935-1940.

Kellogg, R.M. 1982. Coming to grips with wood quality. For. Chron. 58(6):254-257.

Mark, R.E. 1967. Cell Wall Mechanics of Tracheids. Yale University Press, New Haven. p.163-169.

Megraw, R.A. 1985. Wood Quality Factors in Loblolly Pine. TAPPI Press, Atlanta. p.68-75.

Megraw, R.A. 1986. Douglas-fir wood properties. In: Douglas-fir: Stand Management for the Future. C.D. Oliver, D.P. Hanley and J.J. Johnson, ed. Institute of Forest Resources Contribution No.55. p.91.

Richardson, S.D. 1964. The external environment and tracheid size in conifers. In: The Formation of Wood in Forest Trees. Simmerman, M., ed. Academic Press, New York. p.367-388.

Wardrop, A.B. 1951. Cell wall organization and the properties of the xylem 1. Cell Wall Organization and the Variation of Breaking Load in Tension of the Xylem in Conifer Stems. Aust. Jour. Sci. Res. Series b - Biological Sciences. 4(4):391-414.

Zobel, B. and J. Talbert. 1984. Applied Forest Tree Improvement. John Wiley and Sons Inc., Toronto. p.396.

CHAPTER 5

Strength and Stiffness of Dimension Lumber

J.D. Barrett *Faculty of Forestry, University of British Columbia*
R.M. Kellogg *Wood Science Department, Forintek Canada Corp.*

Introduction

The state of research on the strength and stiffness properties of wood from managed stands has recently been reviewed by Barrett and Kellogg (1986). These properties of both juvenile and mature wood have been studied, using for the most part small, clear specimens, and a number of researchers, most notably Littleford (1961), Bendtsen (1978), Pearson and Gilmore (1980), Pearson and Ross (1984), Walford (1985), Senft *et al.* (1985) and Pearson (1988) have demonstrated the lower strength and stiffness of juvenile wood compared to mature wood in southern pine and Douglas-fir. Studies carried out on structural size members (Moody, 1970; Gerhards, 1979; Fight *et al*, 1985; Barrett and Kellogg, 1986) show that the reduction in the strength and stiffness of juvenile wood is equally evident in lumber size specimens of these same species.

These studies provided an awareness that the bending strength and stiffness properties of second-growth lumber might be sufficiently different from the properties of current lumber production to eventually affect design code properties. The purpose of the present study was to undertake, by in-grade testing, a comprehensive evaluation of these properties of second-growth Douglas-fir dimension lumber.

Materials and Methods

Lumber produced in the conversion study described in Chapter 7 was sorted into categories of size and grade, with the material kept separate by the six study sites. Strength tests were confined to the 2 x 4 material and to two grade categories; Select Structural and a combined sort of No. 2 and No. 3 visual grades of dimension lumber. The position of the test pieces was taken into consideration by sorting material according to log position, (top, middle, and butt) and three radial position categories based on the proportion of juvenile wood. These juvenile wood classes were as follows: zero to 10 percent, 40 to 60 percent and 90 to 100 percent. The objective was to select 30 test pieces from each of the 18 classifications of grade (2), log position (3) and percent juvenile wood (3) for each of the six study sites. It was found that filling all of these cells was not feasible. For example, practically all material produced from the top logs was defined as 90 to 100 percent juvenile wood so that there simply was no material available for the other juvenile wood categories. It was also found that since the goal of the conversion study was to maximize lumber value recovery, the volume of 2 x 4 lumber produced was insufficient for the in-grade property studies. In order to rectify this problem, practically all Select Structural and No. 1 grade 2 x 8 material was resawn into 2 x 4, regraded and resorted.

The selected materials were anti-sapstain treated and trucked to Forintek's Vancouver laboratory. Eight-foot test specimens were cut from the selected test lumber, the grade of each final test piece was checked and a code number indicating site, grade, log position and juvenile wood class added to the end of the piece. All material was then dried to a target moisture content of 12 percent in a dehumidifier kiln under extremely mild drying conditions. The test material was then planed at the Eburne Division of Canadian Forest Products.

The lumber was tested to destruction in bending according to in-grade test procedures (ASTM, 1988). Information was obtained on moisture content, specific gravity, rate of growth, percent latewood, size and location of grade-determining defect, and size and location of the failure-causing defect.

Results and Discussion

Statistical summaries of bending strength, expressed as modulus of rupture (MOR), modulus of elasticity (MOE) and relative density were categorized by log location, juvenile wood class and visual grade. Tables 5-1, 5-2, and 5-3 provide results adjusted to 12 percent moisture content. The summaries contain mean and non-parametric fifth percentile properties, normal upper and lower 95 percent confidence limits for mean relative density, MOE and the non-parametric upper and lower 75 percent confidence limits for the fifth percentile MOR. Explanations and procedures for calculating these properties are described by Cook (1986).

Tables 5-4, 5-5 and 5-6 show the comparable results adjusted to 15 percent moisture content. Confidence intervals for the adjusted MOE values are not shown since they provide no additional insights beyond those possible for the 12 percent moisture content data. The tables indicate those test cells

Table 5-1. Mechanical Properties of Second-Growth Douglas-Fir 2 x 4 Dimension Lumber at 12 Percent Moisture Content By Grade and Juvenile Wood Class - Butt Logs, All Sites Combined

Juvenile Wood (%)	Visual Grade	Sample Size	Relative Density	Relative Density 95% C.I.	MOE mean x 10^6psi	MOE 95% C.I.	MOR mean psi	MOR 5th[1] percentile psi	MOR LCL[2] psi	MOR UCL[3] psi
0-10	SS	195	.545	.537, .553	2.08	2.03, 2.13	11730	6285	5573	7042
	2	150	.535	.526, .544	1.84	1.79, 1.90	8548	3338	3005	3453
	3	30	.548	.527, .569	1.90	1.77, 2.04	8670	1707	1375[4]	3444
40-60	SS	175	.508	.499, .517	2.00	1.94, 2.05	10008	5417	4503	5626
	2	116	.503	.493, .513	1.77	1.70, 1.83	7243	2972	2453	3385
	3	24	.493	.474, .512	1.57	1.45, 1.69	6631	2480	2447	2898
90-100	SS	163	.461	.455, .467	1.68	1.64, 1.73	8074	3555	7482	8173
	2	108	.446	.438, .454	1.44	1.39, 1.48	5744	2078	5397	5733
	3	26	.465	.441, .489	1.45	1.34, 1.57	5156	2284	4077	4938

1. Non-parametric estimate.
2. LCL - Lower 75% confidence limit for 5th percentile: non-parametric
3. UCL - Upper 75% confidence limit for 5th percentile: non-parametric
4. Insufficient data.

Table 5-2. Mechanical Properties of Second-Growth Douglas-Fir 2 x 4 Dimension Lumber at 12 Percent Moisture Content By Grade and Juvenile Wood Class - Middle Logs, All Sites Combined

Juvenile Wood (%)	Visual Grade	Sample Size	Relative Density	Relative Density 95% C.I.	MOE mean x 10^6psi	MOE 95% C.I.	MOR mean psi	MOR 5th[1] percentile psi	MOR LCL[2] psi	MOR UCL[3] psi
0-10	SS	35	.523	.505, .541	2.05	1.95, 2.15	10741	3904	3318[4]	7228
	2	69	.509	.496, .522	1.80	1.72, 1.88	8072	3374	1134	3799
	3	9	.492	.447, .537	1.53	1.29, 1.76	6650	3087[4]	3087[4]	3584
40-60	SS	54	.489	.477, .501	1.95	1.86, 2.03	9136	4799	2996[4]	5662
	2	110	.487	.478, .496	1.67	1.62, 1.72	6515	2668	2167	3060
	3	24	.493	.473, .513	1.63	1.48, 1.77	6089	1913	1845[4]	2233
90-100	SS	144	.455	.448, .462	1.63	1.58, 1.67	7648	3660	3225	4374
	2	163	.457	.450, .464	1.56	1.52, 1.60	6116	2858	2700	3052
	3	42	.443	.434, .452	1.42	1.34, 1.50	5518	2182	1248[4]	2285

1. Non-parametric estimate.
2. LCL - Lower 75% confidence limit for 5th percentile: non-parametric
3. UCL - Upper 75% confidence limit for 5th percentile: non-parametric
4. Insufficient data.

Table 5-3. Mechanical Properties of Second-Growth Douglas-Fir 2 x 4 Dimension Lumber at 12 Percent Moisture Content By Grade and Juvenile Wood Class - Top Logs, All Sites Combined

Juvenile Wood (%)	Visual Grade	Sample Size	Relative Density	Relative Density 95% C.I.	MOE mean x 10^6psi	MOE 95% C.I.	MOR mean psi	MOR 5th[1] percentile psi	MOR LCL[2] psi	MOR UCL[3] psi
0-10	SS	9	.515	.478, .552	1.90	1.73, 2.06	9636	4840[4]	4840[4]	7086
	2	14	.494	.462, .526	1.60	1.42, 1.77	6900	2561[4]	2561[4]	2469
	3	10	.504	.470, .538	1.47	1.14, 1.81	5824	1000[4]	1000[4]	3849
40-60	SS	9	.488	.447, .528	1.80	1.58, 2.01	9060	7197[4]	7197[4]	7364
	2	26	.471	.452, .488	1.50	1.39, 1.61	5205	2032	1850[4]	2472
	3	5	.440	.419, .460	1.35	1.14, 1.55	4107	1908[4]	1908[4]	1908
90-100	SS	137	.450	.443, .457	1.54	1.49, 1.58	7010	3818	2723	3938
	2	135	.454	.447, .461	1.44	1.40, 1.48	5462	2200	1949	2655
	3	34	.436	.424, .448	1.26	1.19, 1.33	4433	1630	1593[4]	2360

1. Non-parametric estimate.
2. LCL - Lower 75% confidence limit for 5th percentile: non-parametric
3. UCL - Upper 75% confidence limit for 5th percentile: non-parametric
4. Insufficient data.

Table 5-4. Mechanical Properties of Second-Growth Douglas-Fir 2 x 4 Dimension Lumber at 15 Percent Moisture Content By Grade and Juvenile Wood Class - Butt Logs, All Sites Combined

Juvenile Wood (%)	Visual Grade	Sample Size	MOE mean x 10^6psi	MOR mean psi	MOR 5th[1] percentile psi	MOR LCL[2] psi	MOR UCL[3] psi
0-10	SS	195	1.99	10738	5997	5393	6629
	2	150	1.76	7918	3388	3069	3497
	3	30	1.82	8047	1734	1371[4]	3488
40-60	SS	175	1.91	9179	5260	4459	5439
	2	116	1.69	6775	3037	2522	3432
	3	24	1.50	6238	2548	2515	2965
90-100	SS	163	1.61	7488	3592	3186	4281
	2	108	1.37	5483	2135	1572	2838
	3	26	1.39	4985	2349	2323	3299

1. Non-parametric estimate.
2. LCL - Lower 75% confidence limit for 5th percentile: non-parametric
3. UCL - Upper 75% confidence limit for 5th percentile: non-parametric
4. Insufficient data.

Table 5-5. Mechanical Properties of Second-Growth Douglas-Fir 2 x 4 Dimension Lumber at 15 Percent Moisture Content By Grade and Juvenile Wood Class - Middle Logs, All Sites Combined

Juvenile Wood (%)	Visual Grade	Sample Size	MOE mean x 10^6psi	MOR mean psi	MOR 5th[1] percentile psi	MOR LCL[2] psi	MOR UCL[3] psi
0-10	SS	35	1.95	9798	3914	3369[4]	6723
	2	69	1.72	7461	3421	1110	3820
	3	9	1.46	6268	3148[4]	3148[4]	3620
40-60	SS	54	1.86	8434	4721	3060[4]	5470
	2	110	1.59	6135	2736	2226	3122
	3	24	1.55	5713	1961	1889[4]	2296
90-100	SS	144	1.556	7127	3690	3280	4343
	2	163	1.49	5811	2925	2769	3114
	3	42	1.36	5279	2245	1234[4]	2351

1. Non-parametric estimate.
2. LCL - Lower 75% confidence limit for 5th percentile: non-parametric
3. UCL - Upper 75% confidence limit for 5th percentile: non-parametric
4. Insufficient data.

Table 5-6. Mechanical Properties of Second-Growth Douglas-Fir 2 x 4 Dimension Lumber at 15 Percent Moisture Content By Grade and Juvenile Wood Class - Top Logs, All Sites Combined

Juvenile Wood (%)	Visual Grade	Sample Size	MOE mean x 10^6psi	MOR mean psi	MOR 5th[1] percentile psi	MOR LCL[2] psi	MOR UCL[3] psi
0-10	SS	9	1.81	6655	4757[4]	4757[4]	6665
	2	14	1.53	4871	2631[4]	2631[4]	2838
	3	10	1.41	4156	1000[4]	1000[4]	3866
40-60	SS	9	1.72	8316	6757[4]	6757[4]	6.894
	2	26	1.43	5010	2075	1894[4]	2541
	3	5	1.29	4025	1955[4]	1955[4]	1955
90-100	SS	137	1.47	6583	3837	2792	3948
	2	135	1.38	5243	2263	2000	2724
	3	34	1.20	4332	1656	1615[4]	2427

1. Non-parametric estimate.
2. LCL - Lower 75% confidence limit for 5th percentile: non-parametric
3. UCL - Upper 75% confidence limit for 5th percentile: non-parametric
4. Insufficient data.

Table 5-7. Mean Relative Density by Juvenile Wood Class Calculated as a Percentage of the 0-10 Percent Juvenile Class Relative Density Values (All Grades Combined)

Log Position	Juvenile Wood (Percent) 0-10	40-60	90-100
Butt	100	93	84
Middle	100	95	89
Top	100	94	90

Table 5-8. Mean Relative Density by Juvenile Wood Class Calculated as a Percentage of the Butt Log Relative Density (All Grades Combined)

Log Position	Juvenile Wood (Percent) 0-10	40-60	90-100
Butt	100	100	100
Middle	95	97	99
Top	93	93	99

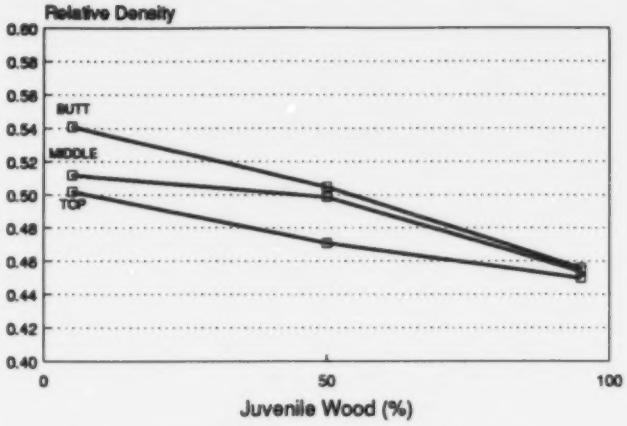


Fig. 5-1 Mean lumber relative density versus juvenile wood percent by log position

where the sample sizes were not sufficiently large to provide an interpolated fifth percentile or confidence limits.

Moisture content adjustments of MOR and MOE were undertaken using the moisture adjustment procedures developed for the North American in-grade testing program. These procedures are at present being balloted for inclusion in ASTM Standard D 2915 - Standard Methods for Evaluating Allowable Properties for Grades of Structural Lumber as a replacement for the current constant percentage strength and adjustment equations (see ASTM D 2915 Section 4.2 and Table 5-4). The proposed adjustments for MOE vary little from those presently recommended in D 2915.

Analyses of Variance (ANOVA) showed a significant variation in all properties with log position, lumber visual grade and juvenile wood percentage. Significant differences at the 5 percent and 25 percent level for the means and fifth percentiles respectively are indicated by non-overlapping confidence intervals in Tables 5-1 through 5-3. Table 5-7 shows changes in mean relative density as a percentage of the relative density for the 0-10 percent juvenile wood class. Average relative density decreases as the percent juvenile wood increases (Figure 5-1). Average relative density also decreases from butt to top log (Table 5-8 and Figure 5-1). There was no significant difference in the average density for different lumber grades but the mean values decrease significantly both with increasing proportion of juvenile wood and with increasing height in the tree.

Trends relating mean MOE and mean MOR to percent juvenile wood are shown in Figures 5-2 and 5-3 for Select Structural and a combined sample of No. 2 and No. 3 grades. There is a consistent and marked decrease in MOR and MOE with an increase in percent juvenile wood for all grades and log locations. This pattern differs significantly between the top log and the butt-middle log relationships. Percentage changes in mean MOE and mean MOR with juvenile wood class are presented in Tables 5-9 to 5-12.

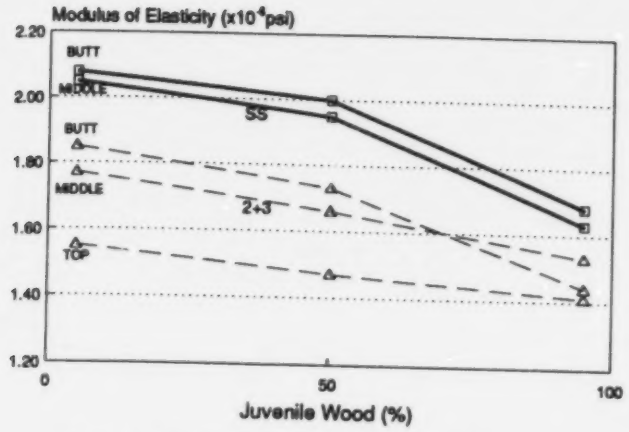


Fig. 5-2 Mean modulus of elasticity versus juvenile wood percent by log position and visual grade

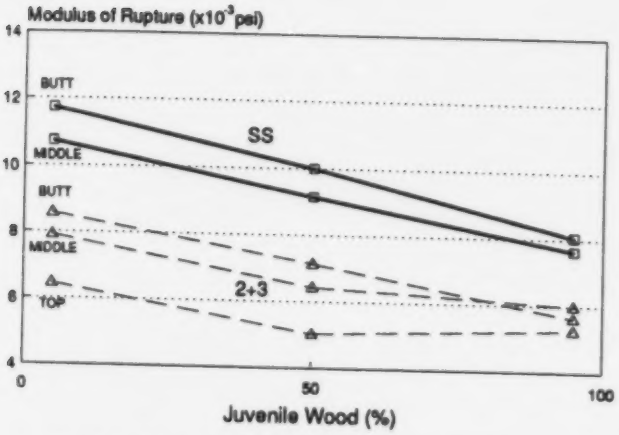


Fig. 5-3 Mean modulus of rupture versus juvenile wood percent by log position and visual grade

Table 5-9. Mean Modulus of Rupture (MOR) by Juvenile Wood Class Calculated as a Percentage of the 0-10 Percent Juvenile Wood Class MOR Values

Log Position	Visual Grade	Juvenile Wood (Percent) 0-10	40-60	90-100
Butt	SS	100	85	64
	2+3[1]	100	83	66
Middle	SS	100	85	71
	2+3	100	81	76
Top	SS	---[2]	---	---
	2+3	100	78	82

1. Grade No. 2 and No. 3 combined
2. Insufficient data for comparison

Table 5-10. Mean Modulus of Rupture (MOR) by Juvenile Wood Class Calculated as a Percentage of the Butt Log MOR Value

Log Position	Visual Grade	Juvenile Wood (Percent) 0-10	40-60	90-100
Butt	SS	100	100	100
	2+3[1]	100	100	100
Middle	SS	92	92	95
	2+3	92	90	106
Top	SS	---[2]	---	87
	2+3	75	70	93

1. Grade No. 2 and No. 3 combined
2. Insufficient data for comparison

Table 5-11. Mean Modulus of Elasticity (MOE) by Juvenile Wood Class Calculated as a Percentage of the Butt Log MOE Values

Log Position	Visual Grade	Juvenile Wood (Percent) 0-10	40-60	90-100
Butt	SS	100	100	100
	2+3[1]	100	100	100
Middle	SS	99	98	97
	2+3	96	96	106
Top	SS	---[2]	---	---
	2+3	84	85	98

1. Grade No. 2 and No. 3 combined
2. Insufficient data for comparison

Table 5-12. Mean Modulus of Elasticity (MOE) by Juvenile Wood Class Calculated as a Percentage of the 0-10 Percent Juvenile Wood Class MOE Values

Log Position	Visual Grade	Juvenile Wood (Percent) 0-10	40-60	90-100
Butt	SS	100	96	81
	2+3[1]	100	93	78
Middle	SS	100	95	80
	2+3	100	94	86
Top	SS	---[2]	---	---
	2+3	100	95	91

1. Grade No. 2 and No. 3 combined
2. Insufficient data for comparison

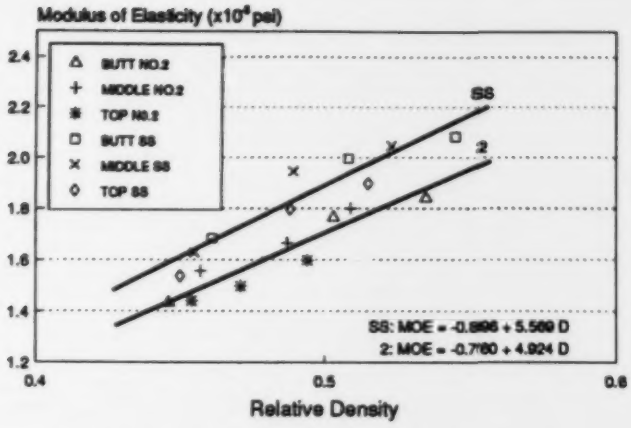


Fig. 5-4 Regression of mean modulus of elasticity versus relative density by visual grade for 2 x 4 dimension lumber

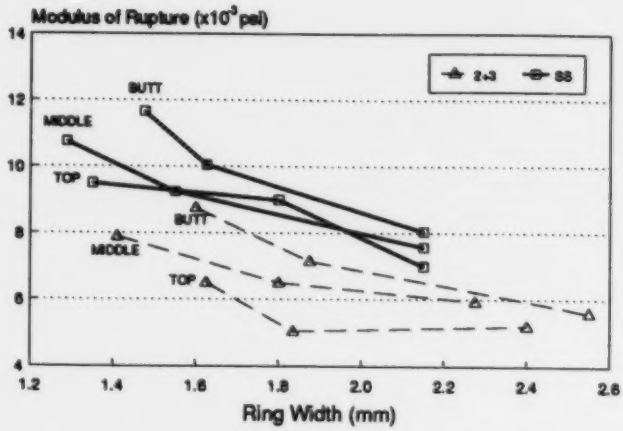


Fig. 5-6 Mean modulus of rupture versus ring width by log position and visual grade

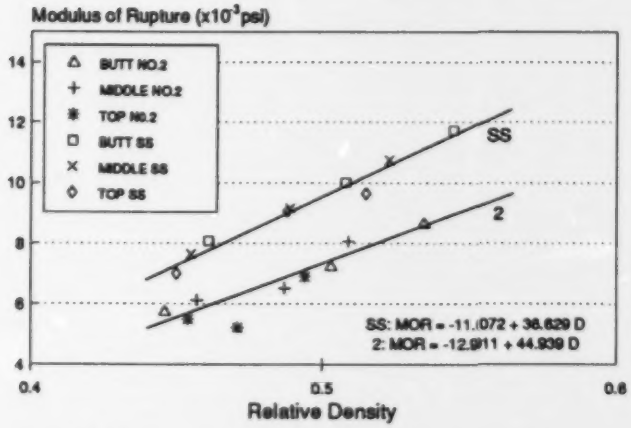


Fig. 5-5 Regression of mean modulus of rupture versus relative density by visual grade for 2 x 4 dimension lumber

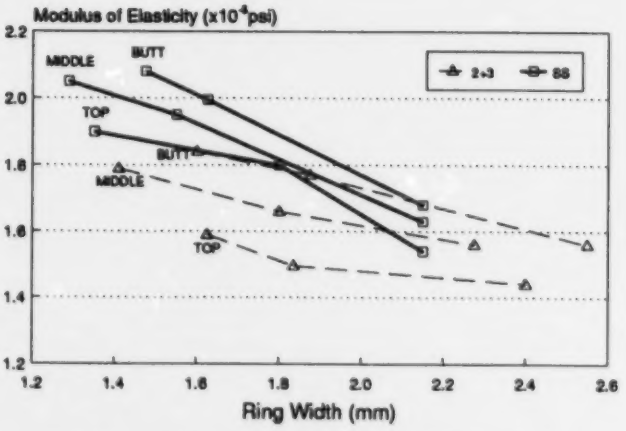


Fig. 5-7 Mean modulus of elasticity versus ring width by log position and visual grade

A significant and positive correlation was found between lumber strength and stiffness on the one hand and the relative density of wood on the other. Mean MOR and MOE results, plotted against mean relative density for Select Structural and No. 2 grades in Figures 5-4 and 5-5, show that a large part of the property variation is explained by relative density differences alone.

Present visual grade specifications exclude wood of rapid-growth rates. The results of this study permit an examination of that growth rate effect. Figures 5-6 and 5-7 show that there is a relationship between ring width and MOR and MOE, respectively. These relationships differ depending on the log position. The fact that the relationship between relative density and both MOR and MOE does not differ with log position within a visual grade (Figures 5-4 and 5-5) suggests that relative density is a more fundamental controlling factor. The lack of a relationship between growth rate and relative density has been discussed in Chapter 1 (see Figures 1-10 and 1-11). The present rings per inch grade restrictions may be a practical way of exerting some grading control on the juvenile wood content of the higher lumber grades because of the normal growth pattern within a tree, but it is clear that ring width alone has little effect on the strength and stiffness of Douglas-fir structural lumber. As the amount of second-growth material being converted increases, the impact of this overly conservative restriction will become greater. Clearly, there is a need to restrict the amount of low density juvenile wood in the higher visual grades, but a growth rate restriction alone has a limited practical value.

The results show a low relative density, MOR and MOE for high juvenile wood percentages. The potential implications of these low properties are assessed by comparing grade mean MOE and fifth percentile MOR results from this study with design properties assigned for visually graded Douglas-fir in the Canadian building codes.

Table 5-13. Design Properties Used In Comparisons With Second-Growth Douglas-Fir

Visual Grade	Comparison A		Comparison B	
	$MOR^{1}_{0.05}$ (psi)	Mean MOE (x 10^6 psi)	$MOR^{2}_{0.05}$ (psi)	Mean MOE (x 10^6 psi)
Select Structural	4440	1.8	4742	1.84
2	2840	1.6	2972	1.58
3	1330	1.5	1798	1.46

1. $R_{0.05}$ = 5th percentile of short term bending strength for 2 x 4 is calculated by multiplying the CSA-086-M84 tabulated design stress by 2.1.
2. 5th percentile of short term strength for Douglas-fir 2 x 4 recommended as a basis for calculated design properties for CSA-086-M89 (under development).

Table 5-14. Design Property Class Assignments Based on CSA-086-M84 and CSA-086-M89 (Projected) Design Properties for 2 x 4 Douglas-Fir

Comparison	Juvenile Wood Class	Log Location: Butt, Visual Grade			Middle, Visual Grade			Top, Visual Grade		
		SS	2	3	SS	2	3	SS	2	3
A	0 - 10	SS	2	E	2	2	E[1]	2[1]	3[1]	E[1]
	40 - 60	SS	2	3	SS	3	3	2[1]	E	E[1]
	90 -100	2	E	E	3	3	E	E	E	E
B	0 - 10	SS	2	3	2	2	3[1]	2[1]	3[1]	E[1]
	40 - 60	SS	2	3	SS	3	3	2[1]	E	E[1]
	90 -100	2	E	E	3	3	E	3	E	E
A+B Combined	0 - 10	SS	2	3[2]	SS[2]	2	3[2]	2[1]	3[1]	E[1]
	40 - 60	SS	2	3	SS	3	3	2[1]	E	E[1]
	90 -100	2	3[2]	E	3	3	E	3[2]	E	E

1. Insufficient data.
2. Value adopted to produce a consistent combined degrade model.

Comparisons of the second-growth results with design properties will vary with the design code chosen and depend on the specific edition referenced. Design property comparisons herein are based on two different sets of design property assumptions (Table 5-13). Comparison A is based on the 2 x 4 Douglas-fir design properties (CSA CAN3-086-M84, 1984). These properties were derived mainly from full-size in-grade tests of 2 x 8 visually graded Douglas-fir dimension lumber and accompanying tests of size (width) effects. The results for size effects allow calculation of design properties for widths other than the 2 x 8 base property. Comparison B is based on 2 x 4 Douglas-fir properties proposed for inclusion in CSA CAN3-086 M89 (1989 Edition). The new Douglas-fir values have been developed from a more recent comprehensive in-grade investigation conducted by the Canadian Wood Council.

The fifth percentile MOR and mean MOE data from the tests of second-growth 2 x 4 tests (Tables 5-4, 5-5, and 5-6) are plotted by visual grade and juvenile wood class for the butt, middle and top logs in Figures 5-8, 5-9, and 5-10. Grade boundaries were established for visual grades Select Structural, No. 2 and No. 3 corresponding to the mean MOE and fifth percentile MOR from Table 5-9. The "corners" of the grade boundaries for comparison B are shown with a "+" in Figures 5-8, 5-9 and 5-10. The objective, then, is to determine if visually graded dimension lumber produced from each of the log location and juvenile wood classes has short term strength properties which meet or exceed those currently claimed for the same visual grade based on in-grade testing of the population.

The mean MOE and fifth percentile MOR obtained for each visual grade and juvenile wood class combination are compared to the grade boundaries. For example, Select Structural properties from the butt log in juvenile wood classes 0-10 and 40-60 meet or exceed the properties at the grade boundary limits established for Select Structural grade in both comparisons A and B. Lumber from the butt log which meets the Select Structural visual grade requirements has mechanical properties sufficient to warrant a Select Structural design property grade. Accordingly, we infer that Douglas-fir second-growth as tested would meet the minimum requirements for design properties at present established for Douglas-fir as well as the values proposed for the 1989 CSA 086 design code. Select Structural visual grade lumber from the butt log in juvenile wood class 90-100 does not have properties that meet or exceed the grade boundary limits; consequently, the Select Structural visual quality material is assigned to a No. 2 design property grade.

Individual comparisons for each juvenile wood class, log location and original second-growth visual grade are summarized for comparison A and B in Table 5-14. Comparisons A and B show the individual design property grades obtained by strict application of the grade boundary procedure. The third series of design property grades shown as "A+B" in Table 5-14 represents a combined assessment based on the design property grades assigned in the two previous comparisons. For the combined assessment the results have been smoothed, recognizing the relatively small sample sizes available and the simplified approach for design property grade assignment.

The design property grade assignments have been made assuming that the visual grades are produced as pure grades and are segregated by juvenile wood class. This approach is taken to isolate the potential influence of juvenile wood and

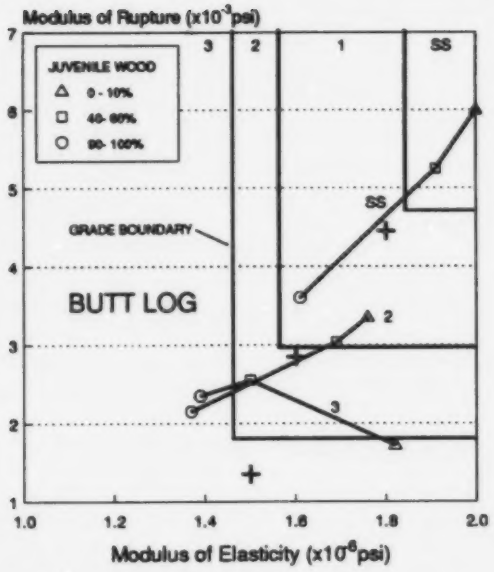


Fig. 5-8 Comparison of estimates of lumber strength and stiffness with CSA-086-M89 visual grade design properties for butt logs

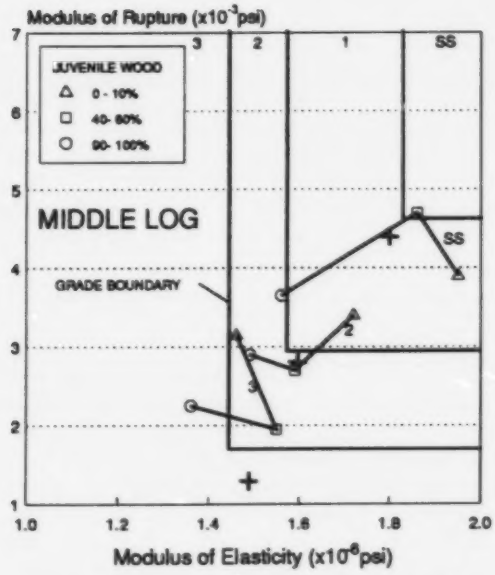


Fig. 5-9 Comparison of estimates of lumber strength and stiffness with CSA-086-M89 visual grade design properties for middle logs

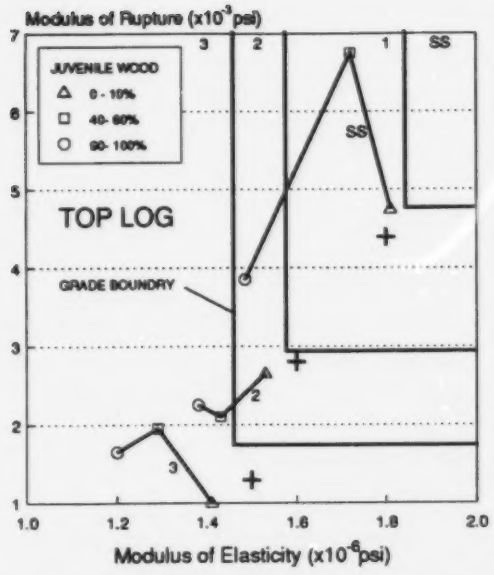


Fig. 5-10 Comparison of estimates of lumber strength and stiffness with CSA-086-M89 visual grade design properties for top logs

log location on design properties. These results do not reflect the design values that could be assigned to random samples of visually graded lumber as typically marketed in British Columbia. The properties of visually graded dimension lumber determined by in-grade testing methods form the basis for the design property assessments for Canadian and many other national codes. The properties determined by such test methods are reflected in the design properties shown in Table 5-13.

Conclusions

This study indicates the potential impact of the properties investigated here on design properties, should the industry significantly change log sorting strategies, increase the conversion of second-growth, fast-grown young trees, or change management strategies in a manner that increases production of low density structural lumber. There is a substantial proportion of the lumber from second-growth trees with high stiffness and strength properties that are not recognizable by means of visual grading. By contrast, machine stiffness rating systems provide a direct method of assessing the structural performance capability of each piece of lumber. Thus machine grading systems may be expected to become an increasingly important alternative to the visual grading technology as the proportion of second-growth trees reaching merchantable size increases.

References

ASTM. 1988. Standard test methods for mechanical properties of lumber and wood-base structural material, D 4761-88. In: 1988 Annual Book of ASTM Standards, Vol. 04.09. Philadelphia, PA. 557p.

Barrett, J.D. and R.M. Kellogg. 1986. Lumber quality from second growth managed forests. In: A Technical Workshop: Juvenile wood - What does it mean to forest management and forest products? Proceedings 47309. Forest Products Research Society. Madison, WI. p.57-71.

Bendtsen, B.A. 1978. Properties of wood from improved and intensively managed trees. For. Prod. J. 28(10):61-72.

CSA. 1984. Engineering design in wood (Working stress design), CSA Standards CAN3-086-M84. Canadian Standards Association. Toronto, ON. 206p.

Cook, J.A. 1986. Documentation of the statistical procedures in the Madison, U.S.F.P.L. in grade testing computer program. Forintek Canada Corp. Report. Vancouver, BC. 130p.

Fight, R., T. Snellgrove, R. Curtis & D. Debell. 1985. Bringing timber quality considerations into forest management decisions: a conceptual approach. In: Douglas-fir: Stand Management for the Future. C.D. Oliver, D.P. Hanley and J.A. Johnson, ed. University of Washington, Institute for Forest Resource. Contribution No. 55. Seattle, WA. p.20-25.

Gerhards, C.C. 1979. Effect of high-technology drying on tensile strength of Douglas-fir 2 x 4's. For. Prod. J. 29(3):39-46.

Littleford, T.W. 1961. Variation of strength properties within trees and between trees in a stand of rapid-growth Douglas-fir. Report V-1028. For. Prod. Lab. of Canada. Vancouver, BC. 20p.

Moody, R.C. 1970. Tensile strength of finger joints in pith-associated and non-pith-associated Southern pine 2 x 6's. Res. Pap. FPL 138. USDA For. Ser., For. Prod. Lab., Madison WI. 20p.

Pearson, R.G. and R.C. Gilmore. 1980. Effect of fast-growth rate on the mechanical properties of loblolly pine. For. Prod. J. 30(5):47-54.

Pearson, R.G. and B.E. Ross. 1984. Growth rate and bending properties of selected loblolly pines. Wood and Fiber Sci. 16(1):37-47.

Pearson, R.G. 1988. Compressive properties of clear and knotty loblolly pine juvenile wood. For. Prod. J. 38(7/8):15-22.

Senft, J.F., B.A. Bendtsen and W.L. Galligan. 1985. Weak wood - fast-grown trees make weak lumber. J. For. 83:476-484.

Walford, G.B. 1985. The mechanical properties of New Zealand-grown Douglas-fir. FRI Bulletin No. 94. For. Res. Insti., New Zealand Forest Service, Rotorua, NZ. 14p.

CHAPTER 6

Chemical Properties

E.P. Swan, J.R. Nault, C.R. Daniels and J.A. Cook *Wood Science Department, Forintek Canada Corp.*

Introduction

The objective of the investigation reported here was to characterize the chemical properties of second-growth Douglas-fir, and thereby to identify any potential quality problems related to those properties that industry might encounter in the utilization of managed stands in the future.

A number of researchers have described the variation in chemical properties within Douglas-fir trees: Ritter and Fleck (1926), Kennedy (1961) and Wilson and Wellwood (1965) have discussed lignification, amongst other properties, within increments; Wu and Wilson (1967) have discussed lignification within growth zones; and Kennedy and Warren (1970) have studied both within increment variations and interzonal variations in the wood.

Variations in cellulose and hemicellulose contents across the stem were studied by Kennedy and Jaworsky (1960) and Kennedy and Warren (1970). Kennedy and Jaworsky showed that cellulose content initially increased rapidly as the distance from the pith increased and that the holocellulose percentages increased less rapidly than the cellulose. Kennedy and Warren confirmed these results and were able to show that the rapid increase in the cellulose from pith to bark occurred within the juvenile wood. The holocellulose contents were constant thereafter. As expected, the lignin content trend was the opposite of that observed for the carbohydrates.

Early work on the isolation of Douglas-fir extractives was concerned with the oleoresins (Benson and McCarthy, 1925). More general studies followed (Erdtmann, 1949; Graham and Kurth, 1949; Lewis, 1950) and dihydroquercetin, a major Douglas-fir heartwood polyphenol, was described by Pew (1948). About a decade later Barton and Gardner (1958, 1963) and Hancock (1957) described analytical methods for determining dihydroquercetin and other polyphenols. Isolation of other extractives was performed by Marvel and Wiman (1962) and Foster *et al.* (1980).

The research on extractives themselves, and techniques for their analysis were necessary before variations could be studied. Hale and Clermont (1963) found greater alcohol/benzene soluble extractives in Douglas-fir earlywood than in latewood. However, Campbell *et al.* (1965) found latewood had a consistently higher extractive content than earlywood. They also showed that the distribution of resinous materials depended on the location of the resin canals within the ring. The earlywood contained the major amounts of mixed fatty acids and unsaponifiables (sitosterols). Squire *et al.* (1967) studied the pattern of flavonoid distribution within a single ring. They found maximum values for these compounds in the earlywood. Kennedy and Warren (1970) did not believe that this effect was real because Squire *et al.* had not accounted for weight ratio changes across the ring. Kennedy and Warren studied the yield of dihydroquercetin across the stem and showed the typical increase reached a maximum close to the heartwood/sapwood boundary. Their data confirmed previous work on this compound by Hancock (1957) and Gardner and Barton (1960), who also showed that the vertical location of the maximum within a tree varied from the butt of some trees to the top of others. Variations in the alcohol/benzene soluble extractives have also been studied across the stem. Hale and Clermont (1963) noted a two-fold increase from pith to bark, but Campbell *et al.* (1965) reported the reverse.

The effects of the extractives on other properties have been studied. It was discovered very early that it was difficult to sulfite pulp Douglas-fir heartwood, and this effect was ascribed to the presence of extractives (Chidester and McGovern, 1941; Hodge, 1954; Gardner and Hillis, 1962). It was thought that heat, through its effect on extractives, adversely affected the surface properties of wood and veneer (Mitchell *et al.*, 1953; Currier, 1958; Hancock, 1963). It was also thought that extractives were responsible for some fungicidal effects (Kennedy, 1956), and that some extractives were formed as a consequence of particular fungal infections (Barton, 1967; Hillis and Ishikura 1969a, 1969b). Rogers and Manville (1972) isolated a juvenile hormone mimic from the heartwood.

Materials and Methods

A total of five cross-sectional discs, 7 to 15 centimeters thick, were cut from each of the ten trees sampled at each site; one at breast-height and four others at one-fifth intervals of total height (Figure 1-2). Most of the analyses were performed on incremental samples from the above, but some analyses were performed on composite samples. In particular, within-tree variation was explored using the incremental samples and

between tree variation was investigated using the composite samples.

The chemical characteristics examined were extractives content (alcohol-benzene, alcohol and hot water by soxhlet), lignin and selected extractives contents of incremental samples from positions at breast-height and 20, 40, 60 and 80 percent of total stem height. In addition, composite samples were prepared by taking a pie-shaped wedge from each breast-height disk.

In the preparation of the incremental samples, 5 year increments were delineated on the disk and then separated using a bandsaw. The individual 5 and 10 year increment samples were comminuted in a Wiley mill to pass 40 mesh. Chemical analyses were conducted on selected wood meal samples from 5 year increments from pith to 20 years, 10 year increment samples from 21 years to the cambium, and composite samples from the breast-height discs. Composite samples were cut in a wedge shape from the disk (of varying radius) to yield approximately 100 grams of wood. The wood was comminuted as before and 5 gram subsamples taken for analysis. For the purposes of this report, those samples comprised of sapwood were not included in the analyses, except in the case of the DHQ analyses.

Benzene-alcohol (2:1), alcohol, and hot water extractive contents were determined successively on wood meal samples. The moisture content of each wood meal sample was first determined on a separate sample. A second sample was then extracted in a tared thimble in a large soxhlet apparatus (TAPPI, 1975). The first extraction solvent (for one day) was alcohol-benzene (1:2 v/v) and, after drying and weighing, the second extraction was with alcohol (for one day) and, after drying and weighing again, a third extraction under reflux was with distilled water (for 3 days). The dry weights of the samples following the extractions were utilized in calculating the extractives contents of each sample. Original dry weights of samples were estimated from the moisture contents determined on matching samples.

Subsamples of the wood samples meal were reacted with 72 percent sulfuric acid in a micromodification of the classic Klason lignin determination (ASTM, 1982). The residues were filtered, dried, and weighed to give values for Klason lignin contents.

Subsamples were analyzed from five trees for dihydroquercetin (DHQ). The analysis method involved high performance liquid chromatography (HPLC). These analyses were carried out as follows:

HPLC Analysis for DHQ

DHQ (Weyerhaeuser Corp.) was recrystallized from water/ethanol and dried *in vacuo* at 110°C. The resulting crystals had a melting point of 239°C (Mettler FPL at 2°C/min.). This material was deemed 100 percent pure and it was used as the DHQ standard for the analysis.

A solution of the DHQ standard in ethanol was made to contain 260 micrograms per milliliter of DHQ. This was used to calibrate the HPLC. The standard showed no other peaks. Approximately 0.5 gram samples of wood were extracted in 15 milliliter ethanol in an ultrasonic bath for two to three hours. One microliter of this solution was injected onto the HPLC column.

Chromatographic Conditions:

Column	:	4.6 x 250 mm Spherisorb ODS-1 5
Temperature	:	50°C
Eluant	:	75% 0.2M $NH_4H_2PO_4$ - 25% Methanol (isocratic)
Flow rate	:	1.5 ml/min.
Detector	:	0.02 Absorbance Units Full Scale/-290 nm/risetime 1.0 sec.
Filter	:	gain - 1 / 0.01 Hz cutoff frequency

At the end of each run the column was washed with 75 percent methanol / 25 percent 0.2 M $NH_4H_2PO_4$. The time between analyses was 35 minutes. The method of calculation was external standard, which was the 260 picograms of DHQ calibration solution described above.

Results and Discussion

The incremental samples were studied to obtain data for within-tree variations in chemical properties. These data were collected from a low, medium, and high wood density tree selected by Paprican for the pulp studies on each of these sites. The breast-height composite samples were used to obtain data for between-tree variations.

Within-Tree Variability

Mean and range values for total extractive content by rings from pith and height position for nine selected trees are shown in Figure 6-1. Mean total extractive content generally decreases from pith-to-bark and from breast-height to 80 percent height at the same cambial age. However, it was found that some trees did not exhibit the general pattern indicated by the means. This is evidenced by the ranges shown in Figure 6-1. Compare the large range of values at ages 0 to 5 years (e.g., breast-height range 4 to 30) to the ranges found at other ages (e.g., breast-height age 41-50 range is 2 to 6). The presence of these wide ranges near the pith, particularly in the lower part of the stem, perhaps explains the differences between the findings of Campbell *et al.* (1965) and the findings of Hale and Clermont (1963). It also conforms with the results of a preliminary study (Nault and Swan, unpublished 1985).

The presence of high variability near the pith makes it unwise to establish a single variance measure for total within-tree extractive content. The mean and variance total extractive content depend upon cambial age and height within the stem. These observations will complicate the relationship between the chemical and pulp properties, particularly yield, and must be accounted for in future research work in this area.

Mean and range values for lignin content versus rings from pith by height position for the nine selected trees are shown in

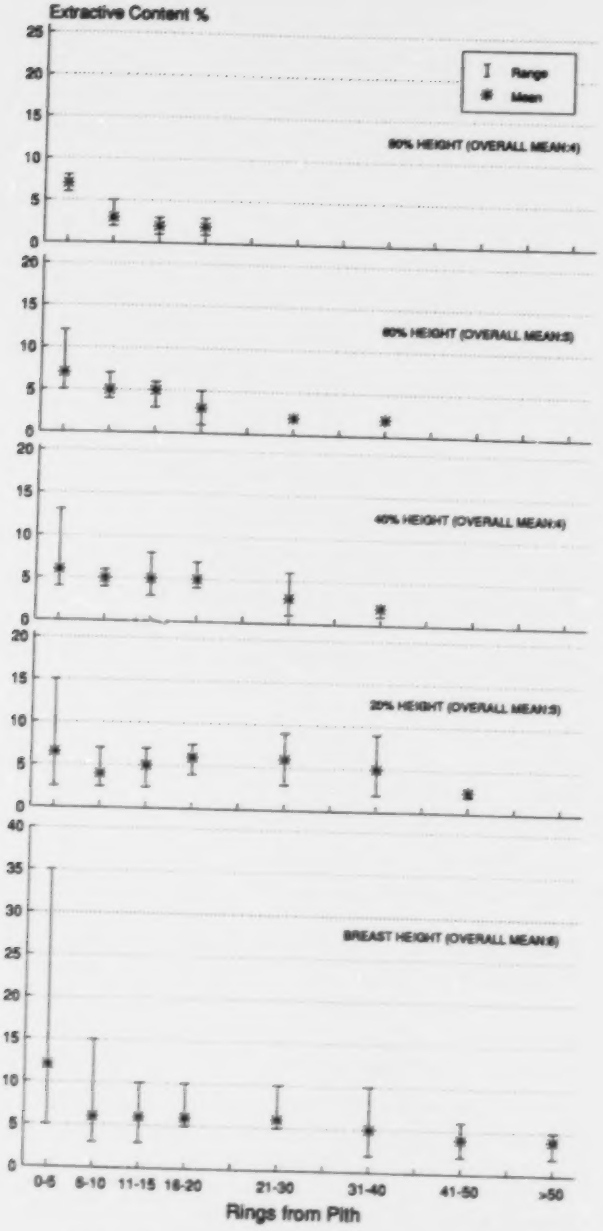


Fig. 6-1 Total extractive content versus rings from pith by sampling height

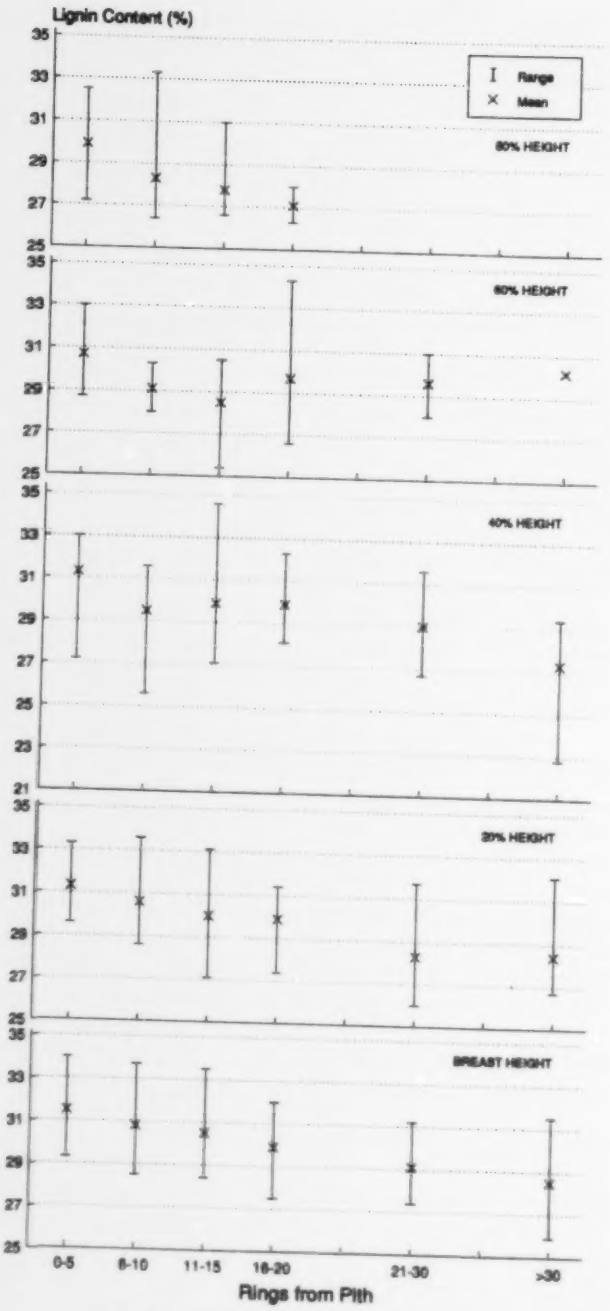


Fig. 6-2 Lignin content versus rings from pith by sampling height

Table 6-1. Comparison of Breast-Height Juvenile and Mature Wood Extractive Contents for Second-Growth Douglas-Fir

Property	Incremental Samples		BH Disks (Chapter 10)			
	Juvenile	Mature	Juvenile		Mature	
Total Extractive Content %	6.7	5.0	8.7	(9.5)	7.4	(8.0)
Lignin Content %	29.9	28.8	29.7	(32.5)	27.6	(29.8)

Table 6-2. Whole BH Disk Total Extractive and Lignin Content

	Mean	Standard Deviation
Total extractive content, %	5	1.1
Lignin content, %	28.8	2.6

Table 6-3. Published Extractive and Lignin Content Data for Douglas-Fir

	Extractive content %	Lignin content %
Bray *et al.* (1940)	3.0 - 14.9	25.3 - 29.6
Wise and Ratcliffe (1947)		28.4
Martin (1949)	11.2	27.2

Figure 6-2. Like total extractive content, these means show a slight decreasing trend from pith to bark and from breast-height to 80 percent height. However, unlike the total extractive content of these trees, the variability (as indicated by the range of values) is relatively constant throughout the trees. The overall mean and standard deviation of all the lignin values measured are 29.5 and 1.9 respectively.

Juvenile-Mature Wood Comparisons at Breast-Height

Mean total extractive contents and lignin contents, weighted by cross-sectional area, for juvenile wood (rings 0-20) and mature wood (rings 21-50) were computed from the breast-height incremental sample properties (Table 6-1). The juvenile and mature wood properties were computed in this way so that the resulting values would be comparable to the juvenile and mature wood properties, based on breast-height disks, reported in Chapter 10.

These numbers are different because the data from Chapter 10 are based on true percentages used by pulping scientists (every component adding to 100). The data presented in this chapter are expressed in the standard way used by wood scientists in which the dry extractive-free wood substance is 100 percent. The recalculated data are in parentheses in Table 6-1.

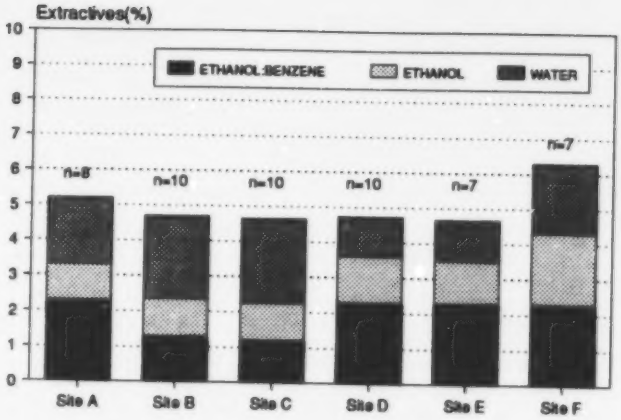


Fig. 6-3 Average extractive content components for individual study sites

Between-Tree Variability

Between-tree variability was investigated using composite samples from a total of 52 breast-height disks from all six sites. The mean and standard deviation for total extractive content and lignin content are shown in Table 6-2.

The variability in lignin content within trees (standard deviation 1.9) is almost as high as the variability between trees (standard deviation 2.6). Published data for mature Douglas-fir trees are shown in Table 6-3.

A comparison of the lignin content values in Table 6-2 and 6-3 shows that the means are comparable; and that there does not appear to be any significant differences between the second-growth and old-growth trees. A similar comparison of the extractives content values is less positive. The second-growth mean was approximately one-half of the old-growth mean reported by Martin (1949), but falls within the range of extractive contents reported by Bray *et al.* (1940).

The contributions of each class of extractives to the total extractive contents, by site, are summarized using bar charts. Figure 6-3 shows the extractives contents for the composite samples for all six sites. The effect of chemical properties on subsequent utilization problems caused by such compounds has not been studied. Between-tree variability in individual extractives are shown in Table 6-4. These data also show the contributions of the various extractives classes to the total extractives contents of second-growth trees. The considerable tree to tree variation observed may prove to be of importance for future research on heritability of extractives.

DHQ Analyses

Selected samples were analyzed for DHQ using an ethanol extract specifically obtained for the analyses (Table 6-5). The DHQ analyses were directly related to the total organic extractives, provided the pith to five-year samples were excluded. In order to judge whether future measurements of

Table 6-4. Contribution of Separate Extractive Classes to the Extractives Content of Second-Growth Douglas-Fir

	Alcohol/Benzene Extractives	Alcohol Extractives	Water Extractives	Total Extractives
n	52	52	52	52
Average	2.0	1.1	1.8	4.9
Standard Deviation	.9	.4	.7	1.1

Table 6-5. Variation of DHQ Content with Height and Radial Position for Five Douglas-Fir Trees

Tree	Position	0-5	6-10	11-15	16-20	21-30	31-40	41-50
E5	BH	1.2	1.5	2.1	2.8	3.2	0.3	
	20	1.1	0.9	1.5	1.4	1.1		
	40	1.3	1.3	1.7	1.6			
	60	2.5	2.0					
	80	3.3						
E9	BH	1.1	1.3	1.5	1.8	2.6	1.5	
	20	1.2	1.5	1.5	2.2	2.8		
	40	1.2	1.5	1.2	1.8			
	60	1.8	1.5	1.9	0.2			
	80	2.9	0.9					
A9	BH	1.3	1.3	1.7	1.9	2.3	2.6	1.0
	20							
	40							
	60							
	80	3.0	1.4					
E7	BH	0.7	1.0	1.0	2.6	2.2		
	20							
	40							
	60							
	80	4.1	0.8					
F6	BH	0.9	1.3	1.9	2.7	3.4	0.8	
	20							
	40							
	60							
	80	3.9						

extractives contents alone will give an estimate of their DHQ content, Figure 6-4 shows the plot of DHQ content versus the material soluble in benzene/alcohol plus alcohol. The equation, DHQ = -0.33 + 0.57 (organic solvent soluble extractives) fits this data with an r^2 value of 0.89. The line does not pass through the origin because of the presence of other extractives such as resin acids (Nault and Swan, unpublished 1985).

Examination of the DHQ data for 16 disks from five trees in Table 6-5 reveals that the DHQ content increases dramatically between breast-height and the 80 percent height for the

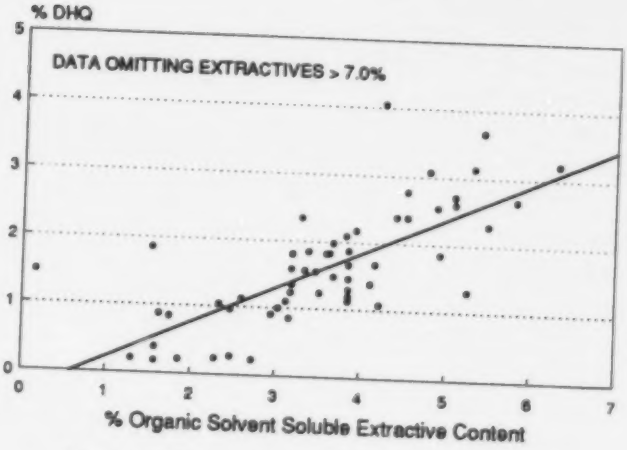


Fig. 6-4 DHQ content versus organic solvent soluble extractive content

material in the first five rings from the pith. In the two trees for which the complete radial series of data points are available a similar progression with height is not found for other radial positions. At breast-height the DHQ content rises from a low point adjacent to the pith, reaches a maximum just before the sapwood boundary and then declines rapidly into the sapwood. The average DHQ content for the outermost sample which would be comprised of almost all sapwood was 0.1 percent. This compared with an average of 1.6 percent for the increment immediately adjacent toward the pith. Chapter 10 reports on the DHQ analyses performed on the Douglas-fir samples used in the pulping research, and discusses the importance of DHQ to color problems in refiner-mechanical pulping.

Conclusions

The polyphenols, such as DHQ, and other alcohol and water soluble extractives are relatively low near the pith and build towards a maximum at the outermost heartwood. The mean total extractives content showed considerable variation between trees. However, the overall mean was approximately one-half of that reported by Martin (1949) and in the lowest part of the range reported by Bray *et al.* (1940) for old-growth trees.

The within-tree variations in the lignin content were similar to previously observed results on this polymer. Lignin content decreased from a maximum near the pith to a constant value in the mature wood at all height positions. Tree-to-tree variation in lignin content was also great. The lignin contents of old- and new-growth trees was approximately the same.

References

American Society for Testing and Materials. 1982. Standard Test Method for Lignin in Wood. D1106-1156. ASTM 22:367-369

Barton, G.M. and J.A.F. Gardner. 1958. Determination of dihydroquercetin in Douglas-fir and western larch wood. Anal. Chem. 30(1):279-281.

Barton, G.M. and J.A.F. Gardner. 1963. Color precursors in Douglas-fir. For. Prod. J. 13(4):216-220.

Barton, G.M. 1967. A new C-methyl flavanone from diseased Douglas-fir roots. Can. J. Chem. 45(4):1020-1022.

Benson, H.K. and D.F. McCarthy. 1925. Composition of oleoresin of Douglas-fir. Ind. Eng. Chem. 17(2):193-194.

Bray, M.W., S.L. Schwartz and J.S. Martin. 1940. Sulphate pulping of Douglas-fir; effect of growth variables on yield and pulp quality, III. Tech. Assoc. Papers. 23(3):232-238.

Campbell, J.R. and E.P. Swan and J.W. Wilson. 1965. Comparison of wood and growth zone resinous extracts in Douglas-fir. Pulp Pap. Mag. Can. 66(10):T248-252.

Chidester, G.H. and J.N. McGovern. 1941. Sulphite pulp from Douglas-fir. Paper Trade J. 113(9):34-38.

Currier, R.A. 1958. High dryer temperatures -- do they harm Douglas-fir veneer? For. Prod. J. 8(4):128-136.

Erdtman, H. 1949. Heartwood extractives of conifers. Tappi. 32(7):305-310.

Foster, D.O., D.F. Zinkel and A.H. Conner. 1980. Tall oil precursors of Douglas-fir. Tappi. 63(12):103-105.

Gardner, J.A.F. and G.M. Barton. 1960. The distribution of dihydroquercetin in Douglas-fir and western larch. For. Prod. J. 10(3):171-173.

Gardner, J.A.F. and W.E. Hillis. 1962. The influence of extractives on the pulping of wood. In: Wood Extractives and Their Significance to the Pulp and Paper Industries. W.E. Hillis, ed. Academic Press. New York p367-403.

Graham, H.M. and E.F. Kurth. 1949. Constituents of extractives from Douglas-fir. Ind. Eng. Chem. 41(2):409-414.

Hale, J.D. and L.P. Clermont. 1963. Influence of prosenchyma cell-wall morphology on basic physical and chemical characteristics of wood. J. Polymer Science 2(C):253-261.

Hancock, W.V. 1957. The distribution of dihydroquercetin and a leucoanthocyanidin in a Douglas-fir tree. For. Prod. J. 7(10)335-338.

Hancock, W.V. 1963. Effect of heat treatment on the surface of Douglas-fir veneer. For. Prod. J. 13(2):81-88.

Hillis, W.E. and N. Ishikura. 1969a. A new flavanone glucoside, poriolin, from Douglas-fir roots. Australian J. Chem. 22(3):483-486.

Hillis, W.E. and N. Ishikura. 1969b. The extractives of the mycorhizia and roots of Pinus radiata and Pseudotsuga menziesii. Australian J. Bio. Sci. 22(6):1425-1436.

Hodge, W.H. 1954. The resistance of Douglas-fir to sulphite pulping. Tappi. 37(3):369-376.

Kennedy, R.W. 1956. Fungicidal toxicity of certain extraneous components of Douglas-fir heartwood. For. Prod. J. 6(2):80-84.

Kennedy, R.W. and J.M. Jaworsky. 1960. Variation in cellulose content of Douglas-fir. Tappi. 43(1):25-27.

Kennedy, R.W. 1961. Variation and periodicity of summerwood in some second growth Douglas-fir. Tappi. 44(1):161-166.

Kennedy, R.W. and W.G. Warren. 1970. Within tree variation in physical and chemical properties of Douglas-fir. In: Second World Consultation on Forest Tree Breeding, Vol. 1. Washington, DC. FAO, Rome. p393-417.

Lewis, H.F. 1950. Significant chemical components of western hemlock, Douglas-fir, western red cedar, loblolly pine and black spruce. Tappi. 33(6):299-301.

Martin, J.S. 1949. Sulphate pulping of logging and sawmill wastes of old growth Douglas-fir and certain associated species. Tappi. 32(12):534-539.

Marvell, E.N. and R. Wiman. 1962. 4-(p-Tolyl)-1-pentanol in Douglas-fir pulping products. J. Org. Chem. 28(5):1542-1545.

Mitchell, R.L., R.M. Seborg, and M.A. Millett. 1953. Effect of heat on the properties and chemical composition of Douglas-fir wood and its major components. J. For. Prod. Res. Soc. 3(4):38-42, 72-73.

Pew, J.C. 1948. A flavanone from Douglas-fir heartwood. J. Amer. Chem. Soc. 70(9)3031-3034.

Ritter, G.J. and L.C. Fleck. 1926. Chemistry of Wood. IX. Springwood and summerwood. Ind. Eng. Chem. 18(6):608-609.

Rogers, I.H. and J.F. Manville. 1972. Juvenile hormone mimics in conifers. I. Isolation of (-)-cis-4-[1'(R)-5'-Dimethyl-3'-oxohexyl]-cyclohexane-1-carboxylic acid from Douglas-fir wood. Can. J. Chem. 50(11):2380-2382.

Squire G.B., E.P. Swan and J.W. Wilson. 1967. Intra-increment variation in Douglas-fir flavanoids by new technique. Pulp Pap. Mag. Can. 68(9):T431-437.

TAPPI. 1975. Preparation of wood for chemical analyses. TAPPI Standard Method T12 OS-75. 2p.

Wilson, J.W. and R.W. Wellwood. 1965. Intra-increment chemical properties of certain Canadian coniferous species. In: Cellular Ultrastructure of Woody Plants. W.A. Cote Jr., ed. Syracuse University Press, Syracuse, NY. p.551-559.

Wise, L.E. and E.K. Ratcliff. 1947. The identification and determination of D-xylose. Ind. Eng. Chem., Anal. Ed. 19(9):694-695.

Wu, Y.T. and J.W. Wilson. 1967. Lignification within coniferous growth zones. Pulp Pap. Mag. Can. 68(4):T159-161.

PART III: Converting the Resource - Solid Wood

CHAPTER 7

Log and Lumber Yields

G.R. Middleton and B.D. Munro *Research and Development Department, Forintek Canada Corp.*

Introduction

This report presents the results of a log and lumber grade recovery study of approximately 300 rapidly-grown, second-growth Douglas-fir trees selected from the six study sites. The primary objective of this study was to determine how log and knot sizes resulting from rapid tree growth affect lumber grade yields. A further objective was to identify stem distributions of juvenile wood, and to provide lumber for drying and strength tests that would assess the effect of differences in juvenile wood content.

Background

The benefits of stand management have generally been described in terms of improved volumes per hectare, and improved tree size (Mallonee *et al.*, 1974; Crown *et al.*, 1977). These are important considerations, but intensive stand management must be directed toward increasing the quality of timber as well as the volume. In this respect, the benefits of intensive stand management have not been clearly established.

There is little published information on yields from managed forests in British Columbia. A study of lumber products obtained from natural stands of 80, 100 and 150 year old Douglas-fir trees selected from Vancouver Island and the Fraser Valley in British Columbia showed that without intensive management, stands 100 years old and younger will yield negligible amounts of clear lumber (Dobie and McBride, 1964). A study of yields from pruned trees conducted in 1958 (McBride, 1961) showed that butt logs from 49 year old trees pruned 28 years previously yielded an average of 18 percent clear lumber compared to negligible amounts from unpruned logs. Another study of product yields from a mixed stand of Douglas-fir and western hemlock [*Tsuga heterophylla* (Raf.) Sarg.] located on Vancouver Island indicated that pruning done at age 33, which is considered to be very late, had a negative effect on product values (Dobie and Wright, 1978).

In terms of quality and value, perhaps the greatest concern facing stand managers lies with the increase in the proportions of juvenile wood in rapidly-grown trees. Paul (1959) noted that the stand management objective of rapid tree growth conflicted with the wood quality objective, which requires small branches and low proportions of juvenile wood. He attributed the formation of juvenile wood to a vigorously growing crown and suggested that early tree growth should be restricted. He further suggested (Paul, 1957) that strength and quality limitations associated with juvenile wood in second-growth timber were exaggerated, but also considered that too little attention was given to remedial and management practices that could compensate for the limitations.

The possibility of controlling the percentage of juvenile wood by slow-growth was rejected by others as biologically unjustified and not economically practical (Zobel *et al.*, 1972). They noted that the formation of juvenile wood was related to age and not to rate-of-growth and suggested that as increasing volumes of fast-grown managed stands are converted, mills will simply have to find ways to convert and market the material profitably in order to prosper.

It is clear, from this brief review, that many questions regarding appropriate stand management strategies remain unanswered. It is hoped that this study, through its contribution to the development of a stand management and conversion model, will help provide these answers.

Materials and Methods

Tree Samples

Sample trees were selected from each of six study stands. Practical constraints on sample size dictated a systematic selection of trees to provide an even distribution over a range of 5 centimeter diameter-at-breast height (DBH) classes. Initially set at 25 to 65 centimeters, this DBH range was narrowed to 30 to 65 centimeters to obtain a greater volume of lumber for drying and strength tests. Seven trees selected at the Ladysmith site were smaller than 30 centimeters DBH and consequently reduced the average DBH of trees in that selection group.

Trees were selected at random with respect to characteristics other than DBH, but severely deformed trees were excluded from the sample because they would not contribute to the study objective. Each tree selected was tagged with a tree number. The final tree sample consisted of 299 trees.

Tree variables measured or tallied according to standard BCMOFL cruising procedures (BCMOF, 1980a) included the following:

- Diameter-at-breast height
- Total height
- Lean and sweep (degrees)
- Height to the live crown and first dead stub
- Number of clear quarters in first two 5 meter logs
- Presence of dead or broken top
- Location by tree thirds of pathological indicators:
  - conk
  - blind conk
  - fork
  - crook
  - scars
  - frost cracks

The sample trees were felled, and bucked to a 10 centimeter top, using standard bucking rules at each site. Preferred lengths were 10.0 and 12.4 meters, which allowed subsequent bucking into 16 and 20 foot mill-run lengths with adequate trim allowance. Each merchantable log length was identified by tree number and log position. Stump heights were recorded and used to calculate corrected tree ages.

Log Measurements

The sample logs were transported to the mill yard of the cooperating sawmill where they were scaled and graded by qualified BCMOFL scalers in accordance with the B.C. Firmwood Scale (BCMOF, 1980b) which specifies the following measurements:

- Log top and butt radii inside bark to the nearest centimeter;
- Log length to the nearest tenth meter;
- Deduction of decay and voids.

Log volumes were calculated using the Smalian formula:

$$V = (TR^2 + BR^2) \times L \times 1.570796 \times 10^{-4}$$

where:

- V = log volume in cubic meters
- TR = log top radius in centimeters
- BR = log butt radius in centimeters
- L = log length in meters.

Each study log was diagrammed to provide an accurate record of all visible log surface and end characteristics. In particular, the sizes and locations of all knots and knot indicators were recorded. Knots and knot indicators were measured to the nearest half centimeter. Long log lengths were measured to the nearest centimeter and end diameters to the nearest millimeter.

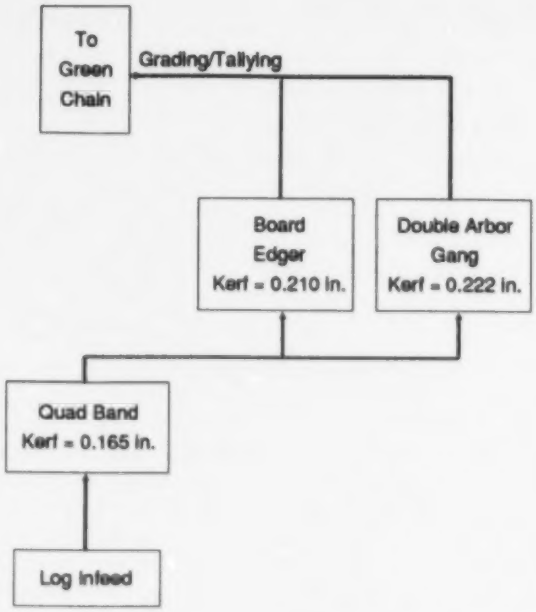


Fig. 7-1 Sawmill machine centers and lumber flow for study mill

The logs were manually bucked into mill-run lengths, after which the small-end diameters were measured to the nearest millimeter to permit accurate classification by log top diameter.

Similarly, the diameter at the 20th growth ring was measured on each log end, and the enclosed area was painted to identify the presence of juvenile wood. The paint was to enable subsequent recognition of the proportion of juvenile wood in each piece of lumber produced from the logs. The twentieth growth ring was chosen as a good approximation of the transition from juvenile wood to mature wood on the basis of an exploratory assessment of pith-to-bark wood density profiles. A more precise definition of the transition has been obtained from the work described in Chapter 2.

Mill Study

The sawmill used for the conversion study was well suited to processing small timber. It featured a quad-band headrig with sharp chain infeed and log rotating capability. Center cants were processed through a double-arbor circular gang saw. Side boards were directed through a three-saw board edger. A schematic of the mill processing equipment with saw kerf sizes indicated is shown in Figure 7-1.

Study logs were processed through the sawmill in color-coded batches of five. The tree identification number of each log was recorded against a sawmill sequence number as the log entered the mill. Lumber from each study log was identified with the appropriate sequence number. Under advisement from the Task Force, the study logs were sawn entirely into

dimension lumber (target size = 1.75 inches). The mill's sawing strategy was to maximize the width of the center cant. The minimum lumber length recovered was 8 feet.

The lumber was pencil trimmed and graded by a qualified industry grader according to rules for structural light framing and structural joists and planks (Paragraphs 123 and 124 of the NLGA Standard Grading Rules for Canadian Lumber NLGA 1980). Lumber grades and dimensions were tallied, and a record was made of the reason for each grade assigned. Pencil trimming was necessary to protect end paint that identified the amount of juvenile wood present in each piece of lumber.

Results and Discussion

Tree Quality

The general characteristics of the stands from which the tree sample was obtained are described in Table 1. The average age, average height, and DBH statistics shown in this table were calculated from trees measured at random to determine the suitability of the sites with respect to desirable (rapid and even) growth rates. They can be considered reasonably representative of the timber in the stands.

Table 7-1 provides age and size statistics for the actual tree samples selected. Table 7-2 shows the extent to which pathological and quality indicators were present in the sample trees. Although these indicators no doubt added somewhat to the overall variation in product yields, their impact was not significant.

Calculated on the basis of tree taper equations used by the BCMOFL (BCMOF, 1983), the predicted average volume of the sample trees was 2.207 cubic meters. The average recovered volume based on the BCMOFL official scale was 2.175 cubic meters.

Individual tree values were derived by matching lumber yields to the appropriate logs and logs to the appropriate trees. Table 7-3 shows how the groups of trees selected from each site differed in terms of average utilizable volume, lumber recovery factor (LRF)[1], and average value. A comparison of the tree statistics in Table 7-1 with the yields and values in Table 7-3 demonstrates how differences in tree characteristics are reflected in timber value. The importance of tree size in determining value is evident, and is further demonstrated by the value to DBH relationships shown in Figure 7-2.

Tree values were calculated on the basis of lumber prices shown in Table 7-4. Although these are based on spot prices for March 1986 (Madison's, 1986), they serve as a good basis for judging relative timber values since they reflect premiums generally paid for higher lumber grades and for wider lumber widths. Premiums for Select Structural were estimated from data previously provided by the industry. Chip and other residual values were ignored in making these tree value comparisons.

[1] Lumber Recovery Factor = $\frac{\text{Lumber Volume (board foot measure)}}{\text{Log Volume (cubic meters)}}$

Table 7-1. Tree Sample Statistics

Location	No. of Trees	Age[1] mean	s.d.	range (years)	DBH mean	s.d.	range (cm)	Height mean	s.d.	range (m)
Ladysmith	49	58	7.6	41-73	44.4	12.2	24-65	34	5.6	22-44
Cassidy	50	63	6.8	50-81	47.2	10.4	30-64	38	4.9	29-47
Campbell River	50	58	5.1	48-77	47.5	10.1	30-63	38	4.5	26-47
Cowichan	50	44	5.1	35-57	48.4	10.0	32-64	31	3.6	21-39
Lizard Lake	50	48	4.1	39-56	47.7	9.6	31-64	34	3.7	25-42
Jordan River	50	55	5.8	42-65	47.6	10.6	30-64	38	4.3	29-46
Combined	299	54	8.7	35-81	47.1	10.4	24-65	36	5.1	21-47

1. Total tree age.

Table 7-2. Pathological And Quality Indicators

Indicator	Occurrence (% of trees)
Sweep	14.4
Fork or Crook	8.0
Lean	7.0
Closed Scar	4.7
Open Scar	0.3
Spiral Grain	-
Conk or Blind Conk	-
Frost Crack	-

Table 7-3. Selected Tree Values

Location	Average Volume[1] (m^3)	Average LRF (fbm/m^3)	Average Value ($/$m^3$)
Ladysmith	2.149	283	53.43
Cassidy	2.242	275	47.28
Campbell River	2.309	272	48.35
Cowichan	2.067	268	49.19
Lizard Lake	2.074	265	47.64
Jordan River	2.210	272	42.97

1. From actual long log scale.

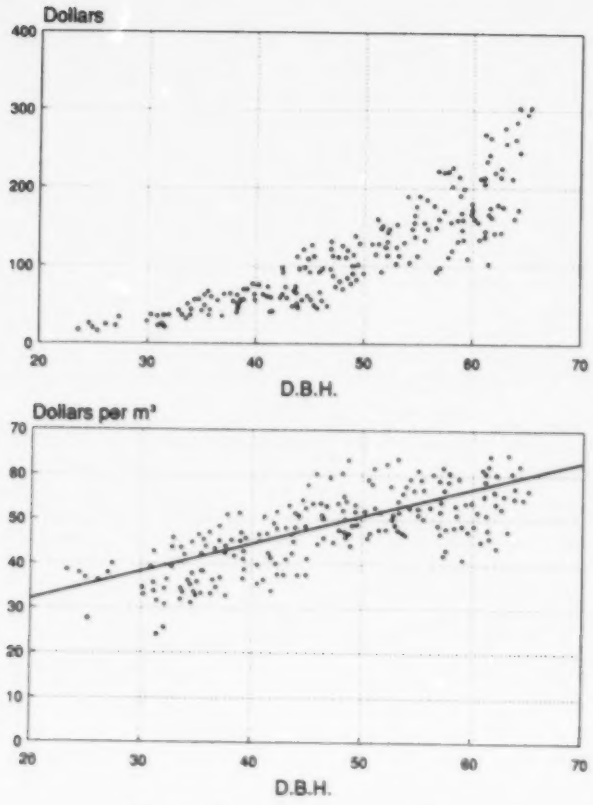


Fig. 7-2 Tree value versus tree size (DBH)

Table 7-4. Lumber Prices

Dimension	Grade				
	Select	No. 1	No. 2	No. 3	Econ.
	($/Mfbm)				
2 x 4	192	178	178	121	53
2 x 6	184	170	170	104	51
2 x 8	189	175	175	89	53
2 x 10	240	222	222	97	66

Log Grade Yields

In the coastal region of B.C., logs are graded for both marketing and appraisal purposes. Log grades are based primarily on log size with additional restrictions placed on knot sizes and defects (BCMOF, 1980b). For the present study, a total of 767 long logs were scaled and graded with a total net volume of 650.1 cubic metres. The scalers made minor length deductions for decay on only four logs. Figure 7-3 shows the distribution of log grades obtained from the tree sample. More than

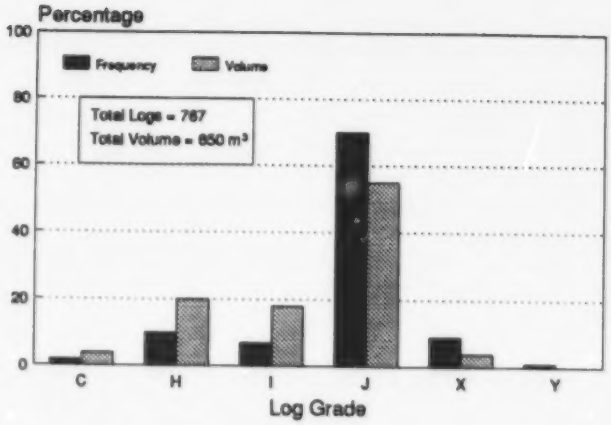


Fig. 7-3 Distribution of log numbers and volume by grade

Table 7-5. Tree DBH Class Distributions of Log Grades

DBH Class (cm)	No. of Trees	Avg. Age (yrs)	Log Vol (m^3)	C	H	I	J	X	Y
				(Percent Volume)					
20.0-24.9	1	45	0.4	-	-	-	100.0	-	-
25.0-29.9	6	57	3.4	-	-	-	100.0	-	-
30.0-34.9	41	51	38.0	-	-	-	99.2	0.8	-
35.0-39.9	41	52	51.6	-	1.7	-	97.8	0.4	0.1
40.0-44.9	41	53	68.8	-	26.0	-	73.1	0.9	-
45.0-49.9	41	54	86.3	1.5	32.7	-	63.5	2.3	-
50.0-54.9	42	56	110.0	3.0	28.3	5.5	60.8	2.5	-
55.0-59.9	42	58	129.0	6.2	20.8	26.6	40.4	5.7	0.3
60.0-64.9	44	56	162.7	6.7	18.4	37.8	31.8	5.1	0.1
	299	54	650.1	3.6	20.7	15.7	56.6	3.3	0.1

half of the total log volume obtained from the tree sample fell into the J grade category, a small good quality sawlog. Table 7-5 shows how log grade yields were distributed within tree DBH classes. Log grade rules applicable to Douglas-fir are provided in Appendix I.

Lumber recovery statistics associated with each grade are shown in Table 7-6. The lumber recovery factor shown for J logs is nearly identical to that obtained for J logs in old-growth studies done previously on the B.C. coast (Middleton and Munro, 1985). The lumber recovery of approximately 300 foot board measure per cubic meter obtained for I, H, and C grade logs is somewhat higher than averages obtained for old-growth, while the recovery factors for X and Y grade logs are substantially lower than those obtained for the same grades in old-growth. These lower recovery factors are due to differences in average log size.

Table 7-6. Log Grade Lumber Recovery Factors

Grade	Number Of Logs	Net Scale (m^3)	LRF mean (fbm/m^3)	s.d.
C	13	23.5	301	29
H	88	134.9	301	28
I	53	101.8	292	30
J	539	367.8	256	55
X	69	21.5	194	67
Y	5	0.7	53	73
Combined	767	650.1	258	61

Table 7-7. Lumber Grade Yields From Log Grades

Log Grade	Lumber Volume (fbm)	Lumber Grade Select %	No. 1 %	No. 2 %	No. 3 %	Econ. %
C	7,104.0	50.1	18.3	17.5	8.7	5.3
H	40,901.3	44.9	21.4	18.2	8.8	6.7
I	29,620.0	33.5	26.6	22.3	10.4	7.2
J	101,178.0	32.1	28.7	22.3	10.0	7.0
X	4,954.0	13.0	37.5	25.9	13.7	9.9
Y	53.0	-	17.4	52.5	30.0	-

Table 7-8. Lumber Recovery Factors For Mill-Run Logs

Diameter Class (cm)	No. of Logs	Net Scale (m^3)	LRF mean (fbm/m^3)	s.d.
10.0 - 14.9	125	15.3	148	64
15.0 - 19.9	161	29.6	191	53
20.0 - 24.9	236	66.2	249	46
25.0 - 29.9	256	99.3	277	41
30.0 - 34.9	218	115.3	292	34
35.0 - 39.9	187	129.4	305	33
40.0 - 44.9	129	113.1	297	29
45.0 - 49.9	62	68.8	295	34
50.0 - 54.9	10	13.3	329	16
Combined	1,384	650.2	260	65

Lumber grade distributions associated with each log grade are shown in Table 7-7. The differentiation in log quality achieved by log grading is clearly indicated by the way the proportion of higher lumber grades declines as log grade declines. The yield of lumber graded No. 2 and Better was 5 to 10 percent lower for second-growth log grades compared to old-growth grades except in Y grade logs where old-growth

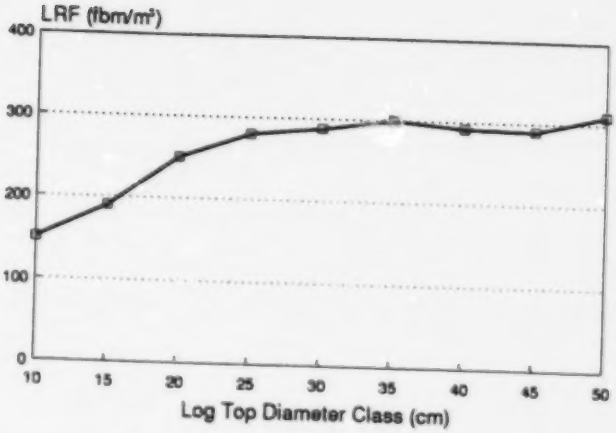


Fig. 7-4 Lumber recovery factor versus mill-run log size

had a yield of 66.9 percent of lumber graded No. 2 and better (Middleton and Munro, 1985), compared to the 69.9 percent obtained here.

Lumber Volume and Grade Yields

Green lumber recovery factors for mill-run logs are shown in Table 7-8 and illustrated in Figure 7-4. The shape taken by the recovery curve over the range of log top diameters is characteristic of recovery curves in general, and reflects what can be achieved with current log processing methods. Improvements in sawmill efficiency are occurring, and can be expected to raise the curve overall, but variability in log quality (shape and roughness) will continue to have the greatest detrimental impact on recovery from small diameter logs. The characteristic shape of this curve helps to make log size, and hence tree size, the most important determinant of tree value.

Total log volume based on short log scale was 650.2 cubic metres. Total lumber volume was 183,811 foot board measure, indicating an overall average lumber recovery factor of approximately 283 foot board measure per cubic meter.

Green lumber grade and dimension yields obtained from the study trees are shown in Table 7-9. The percentages provided in the table indicate how lumber grades were distributed within each lumber width. Select Structural lumber, for example, comprised 12.8 percent of the 2 x 4 volume of lumber recovered. The effect of log top diameter on lumber grade yield is illustrated in Figure 7-5. The figure shows that grades of No. 2 and better accounted for a relatively constant average of approximately 82 percent of all lumber. Increased yields of Select Structural that were obtained as log diameter increased were largely at the expense of reductions in the yield of No. 1 and No. 2 lumber.

Table 7-9. Green Lumber Grade And Dimension Yields

	Size									
	2 x 4		2 x 6		2 x 8		2 x 10		Total	
	fbm	% fbm	fbm	% fbm	fbm	% fbm	fbm	% fbm	fbm	% fbm
Grade										
Select	2,508	12.8	9,296	29.2	20,125	36.5	33,067	42.9	64,996	35.3
No. 1	5,005	25.4	9,436	29.7	15,451	28.0	18,937	24.5	48,829	26.6
No. 2	5,164	26.2	7,430	23.4	11,453	20.7	15,060	19.5	39,107	21.3
No. 3	3,260	16.6	3,880	12.2	5,312	9.6	5,677	7.4	18,129	9.9
Econ.	3,743	19.0	1,744	5.5	2,867	5.2	4,397	5.7	12,750	6.9
Total	19,680	100.0	31,786	100.0	55,208	100.0	77,137	100.0	183,811	100.0

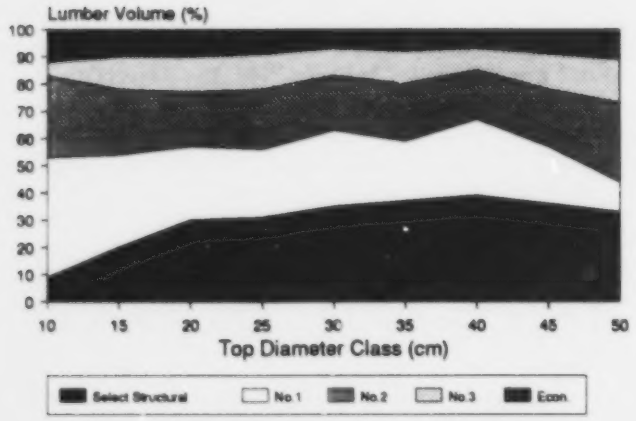


Fig. 7-5 Lumber grade yields versus mill-run log size

Table 7-10. Lumber Defect Contributions To Grade Reductions

Defect	Lumber Affected	
	(fbm)	(%)
None	64,996	35.4
Knots	53,501	29.1
Wane	52,509	28.6
Shake	8,651	4.7
Slope of Grain	1,440	0.8
Rot	876	0.5
Other	1,837	1.0
Total	183,811	100.0

Clearly, differences in lumber value related to log *quality* depend on a premium price for Select Structural. Without this premium the effect that log *size* has on value would become even more important, because premium prices are usually paid for the widest lumber widths (2 x 10s). The effect of log size on the yield of various lumber dimensions is illustrated in Figure 7-6.

It was expected that large branches associated with rapid tree growth would be detrimental to lumber grade yields. The various lumber defects that determined lumber grades were called by the grader and recorded for each piece of lumber. Table 7-10 shows how each of these defects contributed to lumber grade decisions. Approximately 35 percent of the lumber was graded Select Structural and because this was the highest grade obtained, no reason for degrade is noted. Note that the two major reasons for lumber being graded lower than Select Structural were knots (29.1 percent) and wane (28.6 percent). Shake had a minor impact, and all other defects accounted for a negligible volume of degrade. Included in the other category was 164 foot board measure (0.1 percent) of lumber downgraded for rate-of-growth. Since the grader noted only the primary reason for degrade for each piece of lumber, some part of the 65 percent of lumber graded less than select for other reasons may also have failed to meet rate-of-growth requirements. However, the trees were selected for uniform and sustained growth rates from pith to bark. This would generally result in growth rings small enough on average to meet grade requirements.

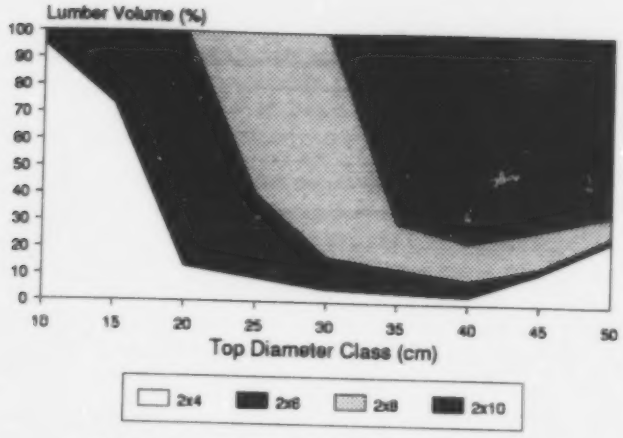


Fig. 7-6 Lumber dimension yields versus mill-run log size

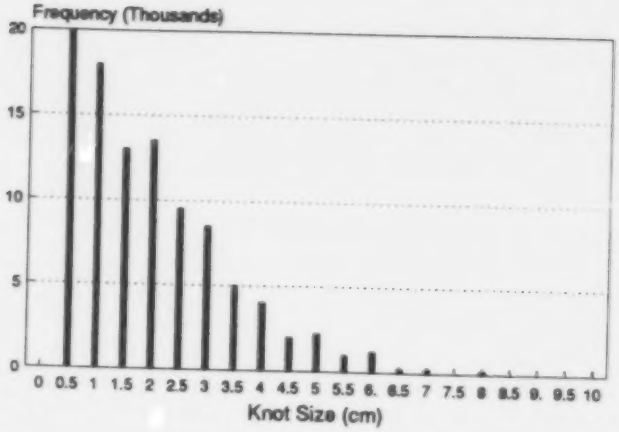


Fig. 7-7 Knot size distribution in study logs

Table 7-11. Select Structural Knot Size Restrictions[1]

Nominal Lumber Width (in.)	Allowable Knot Size			
	Edge		Centerline	
	(in.)	(cm)	(in.)	(cm)
4	3/4	1.91	7/8	2.22
6	1 1/8	2.86	1 7/8	4.76
8	1 1/2	3.81	2 1/4	5.72
10	1 7/8	4.76	2 5/8	6.67

1. NLGA, 1980.

Table 7-12. Knot Index Statistics[1]

Knot Index	mean (cm)	s.d. (cm)	range (cm)
Average Knot Size	1.94	0.56	.64 - 4.17
Average of Largest Four Knots	4.41	1.41	1.25 - 9.75
Average of The Largest Knots Per Quadrant	4.04	1.28	1.00 - 8.88
Largest Knot Per Log	4.92	1.68	1.50 - 11.50

1. n = 752 logs.

These lumber grade results were obtained from green lumber and additional degrade would result if the lumber was kiln-dried. Drying effects were the subject of another Task Force study (Chapter 8).

The Impact Of Knot Size On Lumber Grade Yields

In an effort to quantify the impact of knot size on lumber grade yields, the sizes and locations on the log surface of approximately 100,000 knots were measured and recorded. Figure 7-7 shows how knots were distributed by size for the total tree sample.

Knots were a major determinant of visual lumber grades. In this study they were responsible for nearly 30 percent of the lumber being graded lower than Select Structural. There is no direct linear relationship between knot size and visual grade yield, however, because an acceptable knot size for a given lumber grade is defined by the size of the lumber piece, and by the knot's location within the piece. Knot restrictions for the Select Structural grade lumber, for example, are shown in Table 7-11 and account for the relatively small percentage of 2 x 4 lumber graded Select Structural (Table 7-9).

A number of knot indices were investigated for their potential to provide an estimate of the impact of branch size on lumber grade yields. These knot indices provided a method of classifying a log according to the size and frequency of its knots. They included the following:

(a) the average knot size per log;
(b) the largest knot size per log;
(c) the average of the four largest knots per log; and
(d) the average of the largest knot in each log quarter.

Statistics for each of these indices are provided in Table 7-12. In addition, some ratios of knot surface area to log surface area were investigated, but proved less reliable than less complicated measures. Logs that produced lumber with grade reductions for rot were excluded from all calculations with respect to knots. This reduced the long log sample size from 767 logs to 752 as indicated in the table.

Average knot size proved to be the best measure of the impact of knots on lumber grade yields, followed closely by the average of the four largest knots in each log quadrant. This latter measure was adopted by researchers in New Zealand (Sutton, 1984) who were looking for an estimator that could be easily measured in the field. Ease of measurement has not been a consideration in the present study because knot size information will be obtained from a growth simulation model.

Table 7-13 shows an equation for estimating the proportion of Select Structural lumber associated with logs of a given top diameter and average knot size. Predictions of percent lumber grade yields were required rather than predictions of total grade volumes because a sawmill simulation program is used in the stand management model to determine lumber recovery based on log size. The predictive capability of the equation is low, but it provides some measure of the significant impact that knots have on lumber grade. Predictive equations for total lumber volumes of each grade "explained" considerably more variation (measured by R^2), but merely confirm that lumber volume depends on log size.

Satisfactory equations could not be found for grade percentages other than Select Structural. (Multiple correlation coefficients were typically less than .05). A knot index will not be useful for predicting grades of No. 1, No. 2, No. 3, or Economy lumber. Average grade yields related to log top diameter are more practical predictions of these lower grade yields.

Juvenile Wood

Measurements made of the juvenile cores (first 20 growth rings) were used to calculate stem proportions of juvenile wood by each third of the tree height. These percentages are shown in Table 7-14. Juvenile wood clearly represents a high proportion of the wood that can be expected from rapidly-grown Douglas-fir. The proportion of juvenile wood differed from site to site as shown in Table 7-15. These differences which occurred naturally indicate that stands can be managed to limit its formation. A working stand management and conversion model is needed to consider how this may be accomplished and to predict the economic implications of such a strategy.

It must be emphasized that the results of the conversion study described in this report do not include the impact of juvenile wood on lumber drying and strength characteristics. These implications were considered in other Task Force studies (Chapters 5 and 8). The lumber grade yields provided here must be adjusted accordingly.

A summary of selected tree variables is provided in Table 7-15. The table provides some indication of the different results stand management treatments may be able to achieve. Lumber grade yields are expected to be reduced by high percentages of juvenile wood. These reductions will be greatest where the percentage of juvenile wood is highest.

Table 7-13. Estimating Equation For Select Structural Lumber

Select Structural (%) = 46.85 + .72 TD - 17.03 KI R^2 = .20

Where: TD = log top diameter (cm)
KI = average knot size (cm)
n = 752

Table 7-14. Stem Distribution Of Juvenile Wood

First Third %	Second Third %	Top Third %	Total Stem %
41.0	62.5	85.0	49.0

Table 7-15. Site Distribution Of Selected Tree Variables[1] And Yields

Location	Average DBH (cm)	Average LRF (fbm/m^3)	Average[2] Knot Size (cm)	Average SS Grade (%)	Average Value $/$m^3$	Average Juvenile Wood %
Ladysmith	44.4	283	1.88	45.4	53.43	39.1
Cassidy	47.2	275	2.35	30.5	47.28	35.9
Campbell River	47.5	272	1.73	35.6	48.35	41.8
Cowichan	48.4	265	1.98	33.2	49.19	60.3
Lizard Lake	47.7	268	1.86	38.1	47.64	57.4
Jordan River	47.6	272	1.92	29.7	42.97	59.5

1. Note that these values are not entirely representative of stands on the sites due to systematic sampling by DBH.
2. Average knot size is the average over all logs of the average knot size per log.

Conclusions

In sound second-growth timber, tree value is primarily determined by tree size. This is true because sawmills are more efficient at processing large logs yielding the widest lumber (2 x 10) which commands a premium market price.

Log grades provide an alternative to the extra complication of deriving values for various stand management options on the basis of lumber yields. The results of this study show that present log grade rules provide satisfactory discrimination between log values in terms of lumber grade yields.

Knot size has sufficient impact on lumber value to warrant consideration in stand management plans. However, the impact is very difficult to quantify due to the inherent variability of log quality and sawmill yields in general. Predictions of lumber grade yields will have to be tied primarily to log size.

A compromise between the desire for rapid growth rate and the need for minimum knot size is possible to the extent that lumber strength depends on the ratio of knot displacement to surrounding clear wood area. This allows larger knots to be permitted as lumber width increases. The challenge presented to stand managers is to achieve the optimum balance between tree size and branch size at rotation age.

References

British Columbia Ministry of Forests. 1983. British Columbia Forest Service Coastal Log-Based Appraisal Manual - Effective January 1, 1984. British Columbia Ministry of Forests, Victoria, BC. 25p.

British Columbia Ministry of Forests. 1980a. Forest Service Cruising Procedures and Cruise Compilation. (Revised March, 1983). British Columbia Ministry of Forests, Victoria, BC. 300p.

British Columbia Ministry of Forests. 1980b. Forest Service Scaling Manual. (Revised March, 1983). British Columbia Ministry of Forests, Victoria, BC. 264p.

Crown, M., R.V. Quenet and C. Layton. 1977. Fertilization and Thinning Effects on a Douglas-fir Ecosystem at Shawnigan Lake. Inf. Rep. BC-X-152. Environment Canada, Canadian Forestry Service Pacific Forest Research Centre, Victoria, BC. 36p.

Dobie, J. and C.F. McBride. 1964. Lumber recovery from second-growth Douglas-fir in British Columbia. For. Prod. J. 15(2):55-60.

Dobie, J. and D.M. Wright. 1978. Economics of thinning and pruning - A case study. For. Chron. 54(1):34-38.

Madison's Canadian Lumber Reporter. 1986. Vancouver, BC. 36(9).

Mallonee, E.H., R.F. Strand, D.S. De Bell and J.Y. Lin. 1974. Effects of Fertilization on Growth of Young Douglas-fir Plantations near Campbell River, British Columbia. For. Res. Note No. 3. Crown Zellerbach, Central Research, Camas, WA. 6p.

McBride, C.F. 1961. Lumber grades recovered from pruned Douglas-fir trees. For. Chron. 37(4):390-393.

Middleton, G.R. and B.D. Munro. 1985. Product Outturn Values For British Columbia Coastal Log Grades: An Information Report. Canadian Forestry Service Contract Report No. 40-12-424. Forintek Canada Corp. Vancouver, BC. 22p.

National Lumber Grades Authority. Revised 1980. Standard Grading Rules for Canadian Lumber, NLGA, Vancouver, BC. 206p.

Paul, B.H. 1957. Second Growth Is Good. Rep. No. 2083. USDA, Forest Service, Forest Products Laboratory, Madison, WI. 9p.

Paul, B.H. 1959. The Effect Of Environmental Factors On Wood Quality. Rep. No. 2094. USDA, Forest Service, Forest Products Laboratory, Madison, WI. 6p.

Sutton, W.R.J. 1984. New Zealand Experiences With Radiata Pine. (Paper presented as the H.R. MacMillan Lectureship in Forestry, February 23, 1984.) University of B.C., Faculty of Forestry, Vancouver, BC. 21p.

Zobel, B.J., R.C. Kellison and D.G. Kirk. 1972. Wood Properties of young loblolly and slash pines. In: Proceedings of a Symposium on the Effect of Growth Acceleration on the Properties of Wood. USDA, Forest Service, Forest Products Laboratory, Madison, WI. 245p.

CHAPTER 8

Kiln Drying Lumber

J.F.G. Mackay *Research and Development Department, Forintek Canada Corp.*

Introduction

The successful conversion of second-growth and rapidly-grown forests in British Columbia will require the finished products to be of the highest possible value consistent with the costs of production. This likely points to a preference for lumber products to be marketed kiln dried rather than green. Experience with lumber sawn from young, plantation-grown softwoods from elsewhere suggests that some properties of rapidly-grown wood adversely affect drying behavior. Severe warp of juvenile wood during drying has been described by Mackay and Rumball (1971), Christensen and Gough (1975) and Shelley *et al.* (1979) for three *Pinus* species. In anticipation of the conversion of second-growth coastal Douglas-fir logs of this type it is important to be aware of potential problems during kiln drying so that corrective procedures can be implemented. As a first step in this direction, the present study attempts to determine the drying properties of second-growth Douglas-fir lumber.

Materials and Methods

The lumber dried in this study was produced in the sawmill log and lumber trade recovery study (Chapter 7). All 2 x 6 lumber, 12 feet and longer, from two eastern and two western sites was anti-sapstain treated, shipped to the laboratory and sampled for use in the drying study. Sampling was designed to obtain pieces representing the east and west sides of Vancouver Island, two lumber grades and three levels of juvenile wood. The number of pieces in these respective categories are shown in Table 8-1.

The kiln load of 7,000 foot board measure was assembled as follows: all lumber was trimmed to 8 feet in length by removing at least 2 feet from each end to eliminate the effect of drying during storage. A moisture content section was sawn from every tenth piece to provide an estimate of average green moisture content. Lumber was randomly selected from each of the 12 groups (Table 8-1) and loaded onto kiln cars 14 pieces wide and 30 rows high, with 1 x 3 strips at 4 foot centers between rows. Visible splits, checks and warp were measured and noted.

The drying schedule can be seen in Table 8-2. Air velocity through the load was 500 feet per minute with direction of flow reversed every four hours. Following drying to a target average moisture content of 15 percent, the load was cooled and moisture contents were measured in all pieces with a resistance-type moisture meter and insulated electrodes to a depth of 3/8 inch at a distance of 24 inches from one end. All defects were measured and noted.

Table 8-1. Lumber Pieces Available for Drying Study

Area	Lumber Grade	Percent Juvenile Wood		
		0 - 10	40 - 60	90 - 100
East	Select Structural	107	101	107
	2 & 3	46	38	50
West	Select Structural	40	66	119
	2 & 3	27	43	97

Table 8-2. Kiln-Drying Schedule for Drying 2 x 6 Douglas-Fir Commons

Dry-Bulb Temperature (°F)	Wet-Bulb Temperature (°F)	Time (hr.)
180	165	8
210	190	16
220	190	8
230	190	16
200	190	4
		52

Results and Discussion

Green moisture contents averaged 41.1 percent with a range of 23.1 to 126.1 percent. These values, which showed little difference between east or west areas, are close to averages for the species reported in standard reference texts. Nielson *et al.*, (1985) cite for coastal Douglas-fir, sapwood, heartwood and "mixed", moisture contents of 151, 39 and 45 percent respectively. Kiln-dry moisture content distributions based on

Table 8-3. Moisture Content Distribution After Kiln Drying

Moisture Content (%)	Percent of Pieces
≤ 10	9.2
11 - 14	67.7
15 - 19	18.4
≥ 20	4.7

Table 8-4. Average Warp Developed During Drying of Douglas-Fir Lumber with Varying Proportions of Juvenile Wood

Warp	Grade	Average Warp (in.)		
		Percent Juvenile Wood		
		0 - 10	40 - 60	90 - 100
Cup	SS	0.010	0.022	0.032
	2 & 3	0.010	0.022	0.027
Crook	SS	0.021	0.016	0.019
	2 & 3	0.037	0.042	0.081
Bow	SS	0.049	0.076	0.091
	2 & 3	0.031	0.085	0.173
Twist	SS	0.080	0.137	0.338
	2 & 3	0.140	0.211	0.482

Table 8-5. Percent Increase in Warp with Increasing Percent of Juvenile Wood

Warp	Grade	Percent Increase in Warp over 0 - 10% Juvenile Wood	
		Percent Juvenile Wood	
		40 - 60	90 - 100
Cup	SS	120	220
	2 & 3	120	170
Crook	SS	-24	-10
	2 & 3	14	119
Bow	SS	55	86
	2 & 3	174	458
Twist	SS	71	323
	2 & 3	51	244

Table 8-6. Number of Pieces of Each Grade and Juvenile Wood Class that were Reduced in Grade Due to Twist

Percent Juvenile Wood	Original Grade	Total Pieces Dried	Number of Pieces Reduced to These Lower Grades		
			#2	#3	Econ.
90 -100	SS	226	22	19	6
90 -100	2 & 3	147	--	--	12
40 - 60	SS	167	3	2	0
40 - 60	2 & 3	81	--	--	1
0 - 10	SS	147	0	1	1
0 - 10	2 & 3	73	--	--	1

species- and temperature-adjusted moisture meter readings are shown in Table 8-3. No relationship of moisture content to percent juvenile wood, grade or log source was observed.

Drying degrade in the form of checks and splits was very slight across all grades and levels of juvenile wood. Warp, particularly twist, was a major degrading factor. Average warp values are shown in Table 8-4. There was a strong tendency for warp to increase with increasing proportion of juvenile wood, as shown in Table 8-5. The grade limit for twist in 2 x 6 x 8 feet Select Structural and No. 1 lumber is 0.5625 inch, and while the average twist in Select Structural wood with 90 to 100 percent juvenile wood was only 0.338 inch, Table 8-6 shows that over 20 percent of these pieces had twist in excess of the grade limit causing a drop to grade 2, 3 and Economy.

Conclusions and Recommendations

Conventional kiln-drying schedules and practices will result in twist in second-growth Douglas-fir lumber that contains high proportions of juvenile wood. Methods used elsewhere to limit the problem in other species include the use of high temperatures to plasticize wood, and decreased sticker separation in conjunction with spring-loaded clamps or top-loaded concrete weights to restrain movement during drying. These methods should be examined to develop a cost-effective means of reducing degrade losses in this material.

References

Christensen, F.J. and D.K. Gough. 1975. Control of drying distortion in framing from young plantation Slash pine. Report No. 44. CSIRO Division of Building Research, Melbourne, Australia. 38p.

Mackay, J.F.G. and B.L. Rumball. 1971. Drying of distortion prone juvenile core Radiata pine for house studs. Aust. Timber J. 37(6):43-57.

Nielson, R.W., J. Dobie and D.M. Wright. 1985. Conversion factors for the forest products industry in western Canada. Special Publication No. SP-24R. Forintek Canada Corp., Vancouver, BC. 92p.

Shelley, J.R., D.G. Arganbright and M. Birnbach. 1979. Severe warp development in young-growth Ponderosa pine studs. Wood and Fiber 11(1):50-56.

CHAPTER 9

Heartwood Treatability

J.N.R. Ruddick *Faculty of Forestry, University of British Columbia*

Introduction

Changes in the forest resource of Canada are leading inevitably to an increased use of second-growth Douglas-fir, the heartwood of which is less durable than that of old-growth Douglas-fir because of its lower extractive content. The effective preservative treatment of this heartwood will therefore be very important, particularly for sawnwood products, such as bridge timbers, which are traditionally produced from this wood species.

Bramhall (1966) reported that the permeability of Douglas-fir heartwood lumber produced in British Columbia is extremely variable. Heartwood of Douglas-fir grown east of the Coast Range was found to be refractory, i.e., untreatable, whereas that from Vancouver Island was much easier to pressure impregnate with preservative. This conclusion has been supported by several other investigations, including those undertaken by Miller and Graham (1963) and Weaver and Levi (1979). However, all previous studies have examined the treatability of heartwood without reference to the type of heartwood, i.e., juvenile and mature.

The relative treatability of mature and juvenile Douglas-fir heartwood will be very important in decisions for converting the resource. Since second-growth material has a much greater proportion of juvenile heartwood, which is less dense and has a lower extractive content, some improvement in heartwood treatability may be anticipated.

This study compares the permeability of juvenile and mature heartwood when pressure impregnated with chromated-copper-arsenate (CCA) and ammoniacal-copper-arsenate (ACA).

Materials and Methods

Forty-two boards of 100 percent juvenile heartwood and forty boards of 100 percent mature heartwood were selected for the study. The test samples (120 x 5 x 15 cm) were sawn from kiln-dried stock available from the drying study (Chapter 8). The dry lumber was stored under cover for approximately three months prior to treatment. Prior to preservative treatment the lumber was incised on one face to improve preservative penetration. The incision depth varied but was typically 7 to 9 millimeters. Each board was sawn in two to produce matching pieces (60 centimeters in length), one piece for treatment with CCA and the other with ACA.

The preservative treatments were applied using a full cell process, the details of which are shown in Table 9-1. The juvenile and mature heartwood samples were treated together in the same charge. Following treatment, each of the boards was sampled to measure preservative penetration. Instead of boring each sample, a thin slice was removed from the full width of the board and cut at the center avoiding knots and incisions. The cut surface was then sprayed with chrome azurol S reagent to show the presence of the copper component in both ACA and CCA. Penetrations were measured from the inner (incised) heartwood face. An evaluation was also made of the integrity of the preservative treatment at 5 millimeters for CCA and 10 millimeters for ACA from the board surface. These distances, selected after examination of the samples, were chosen as being close to 50 percent of the limit of preservative penetration. This would maximize the ability to detect any differences between the treatability of the juvenile and mature heartwood. Samples removed from each board were combined for a single composite assay using energy dispersive x-ray analysis. It should be noted that to determine the retention in terms of the weight of preservative per unit volume of wood, average densities of mature and juvenile heartwood were used. Based upon an inspection of the samples, it was concluded that they were produced from the lower half of each tree. Consequently, average densities of 0.45 (juvenile) and 0.52 (mature) were used for the assay.

Results and Discussion

The preservative penetration and retention data for both the CCA and ACA treatments are shown in Table 9-2. Although the treatment schedules were similar, the ACA treatment was found to be superior to the CCA treatment in that the average penetrations and retentions for both juvenile and mature heartwood were higher. However, the treatability of juvenile and mature heartwood, in terms of penetrations and retentions, was not statistically different for either preservative.

Comparison of the data with the penetration requirements of the Canadian lumber standard (CSA 080.2, 1985), as shown in Table 9-3, showed that 50 percent of the CCA-treated juvenile Douglas-fir heartwood lumber did not achieve the minimum penetration of 10 millimeters, whereas only 5 percent of the

Table 9-1. Treatment Parameters

Preservative:	CCA-type C 2.3% (oxides on a wt/wt basis)
Treatment Process:	Full Cell; initial vacuum 40 min. at -100 kPa, pressure 1040 kPa for 4.25 hours (pressure applied in 350 kPa increments over 15 min.); final vacuum 20 min. at -75 kPa.
Preservative:	ACA 2.3% (oxides on a wt/wt basis)
Treatment Process:	Full Cell; initial vacuum 35 min. at -100 kPa; pressure 1040 kPa for 4.25 hours (pressure applied in four increments, 350, 520, 700 and 1040 kPa, over 35 min.); final vacuum 20 min. at -75 kPa.

Table 9-2. Preservative Penetrations and Retentions in Mature and Juvenile Douglas-fir Lumber

Preservative	Heartwood Type	Penetration (mm)	s.d.	(%)[1]	s.d.	Retention (kg/m^3)
CCA	Juvenile	9.5	6.2	64	17	15.2 ± 0.8
	Mature	11.8	5.8	49	14	14.4 ± 0.7
ACA	Juvenile	18.4	6.9	70	15	21.6 ± 1.1
	Mature	17.0	4.9	65	14	19.9 ± 1.0

1. percent treated wood at a depth of 5 mm

Table 9-3. Percent Conformity with the Penetration Requirements of the Canadian Standard for Lumber (CSA 080.2;, 1985)

Preservative	Heartwood Type	Percent Samples with Penetration greater than 10 mm (%)
CCA	Juvenile	50
	Mature	67.5
ACA	Juvenile	95
	Mature	92.5

corresponding ACA-treated lumber did not show 10 millimeter penetration. Similar differences were noted for the mature heartwood lumber. The CCA and ACA treatment of the lumber would have improved through the use of a more closely spaced pattern than that selected. However, the pattern chosen had the advantage of allowing comparison of the treatment of the two heartwood types.

Conclusions

This study suggests that preservative treatability is not a significant factor in the greater use of second-growth Douglas-fir and that the changes taking place in the utilization of the resource need not affect treatment strategies. Treatment schedules developed from experience to treat sawnwood in compliance with Canadian wood preservation standards will not need to be changed when second-growth lumber or timber is pressure treated.

Recommendations

Additional research should address the relative permeabilities of mature and juvenile Douglas-fir heartwood to oilborne preservatives. Investigations should also examine the influence of sapwood content on the treatability of Douglas-fir roundwood and timber with respect to oilborne and waterborne preservatives.

References

Bramhall, G. 1966. Permeability of Douglas-fir heartwood from various areas of growth in B.C. B.C. Lumberman. 50(1):98-102.

Canadian Standards Association. 1985. CSA 080.2. Pressure treatment of lumber, timber, bridge ties and mine ties by pressure processes. CSA. Rexdale, ON.

Miller, D.J. and R.D. Graham. 1963. Treatability of Douglas-fir from western United States. Proc. Amer. Wood Preserv. Assoc. 59:218-222.

Weaver, F.W. and M.P. Levi. 1979. The treatability of Southern pine and Douglas-fir heartwood with creosote, modified creosote, chromated-copper-arsenate and ammoniacal copper arsenate. Proc. Amer. Wood Preserv. Assoc. 75:176-185.

PART IV: Converting the Resource - Pulp

CHAPTER 10

Density and Chemical Properties of Juvenile, Mature and Top Wood

J.V. Hatton and K. Hunt *Resource Evaluation Section, Pulp and Paper Research Institute of Canada*

Introduction

The most recent Canadian forest inventory (Bonner, 1982) puts the 1981 volumes of softwood and hardwood in the ten provinces at 15.0 and 3.9 billion cubic meters, respectively. In spite of these impressive figures, the forest industry in Canada faces a potential timber supply problem caused by a combination of economically inaccessible wood, an imbalanced age/class distribution of stands and a decrease in productivity on some sites following removal of the old-growth forest. This "falldown" effect can, to some degree, be compensated for by better use of the available resource, increased protection of the resource from insects, disease and fire, and intensive forest management practices.

An intensive management approach will produce a second-growth resource which will be characterized by faster growth rates, reduced rotation times and, therefore, probably smaller log diameters. This would result in a marked increase in juvenile or core wood in the future forest resource.

An extensive data base is available in the literature which compares and contrasts the principal differences in properties between young and old trees or, more specifically, between juvenile wood and mature wood. The reviewed literature was subdivided into the three categories of wood properties, fiber morphology, and pulping and handsheet fiber properties, for both softwoods and hardwoods, and by geographic region.

Despite its extent, the present data base has a number of weaknesses:

- Softwood data have been derived almost entirely from *Pinus* species, whether in the United States or New Zealand.
- Few data are available for Canadian species.
- In the "wood properties" category, only a few attempts have been made to identify specific components of extractives and their roles in pulping and papermaking. This is critical for Canadian woods, such as Douglas-fir, western red cedar and jack pine, where the location and quantities of extractives, such as dihydroquercetin, thujaplicins and pinosylvins, respectively, could have a significant bearing on the bleachability and end uses of mechanical pulps from these species.
- The most striking weakness is that the very comprehensive data available for each of the three categories have generally not been related to each other.

An exception to this are the recent studies on *Pinus radiata* in New Zealand by Kibblewhite (1980, 1982, 1984a, 1984b), Uprichard (1980), and Corson and Lim (1983). These researchers have consolidated wood properties, fiber morphology data, and handsheet fiber properties to provide a clear picture of the potential of juvenile and mature wood fibers in pulping and papermaking.

Although more than 100 references are available on different aspects of pulping and bleaching Douglas-fir, few data are available on the wood and pulping properties of juvenile and mature wood from Douglas-fir. The tensile strength of Douglas-fir wood was found to increase with fiber length and decreasing fibril angle, i.e., with increasing tree age (Wardrop, 1951), and a good correlation was found between tensile strength and fibril angle for both earlywood and latewood specimens from this species (Ifju and Kennedy, 1962). In Douglas-fir the fibril angle was found to decrease from 37° to 7° from the 1st to the 30th annual ring (Erickson and Arima, 1974). Kraft pulps from Douglas-fir tops consisting of juvenile wood had lower yield, equivalent burst index and breaking length, but lower tear index than those from full boles consisting of juvenile and mature wood (Hatton and Keays, 1972). The superior burst index and breaking length of kraft pulps from both 20 to 23 (Bublitz, 1971) and 13 year old (Bublitz and Chia, 1974) Douglas-fir thinnings relative to those from mature wood suggested their possible use for linerboard. In addition, there is evidence that, relative to

mature wood, juvenile wood from this and similar species (e.g. southern pine) have morphology better suited to paper production (North Carolina State U., 1984), and that the color of sapwood from second-growth material is lighter than that from old-growth trees.

In taking the same in-depth approach as the New Zealand workers, the Pulp and Paper Research Institute of Canada's (PAPRICAN) objective as part of this Task Force effort is to characterize the quality of pulps from juvenile wood and mature wood of Canada's second-growth forests.

The research effort here takes three approaches:

- Quantifying the physical and chemical properties of juvenile wood and mature wood.
- Establishing relationships between wood density and fiber properties of juvenile wood and mature wood with mechanical and optical properties of chemical and mechanical pulps.
- Quantifying the effects of differences in the processing and pulping of chips from juvenile wood and mature wood in the production and refining of chemical and mechanical pulps, relating these to fiber properties and thereby explaining how the various wood and fiber quality characteristics affect the pulp properties.

This chapter presents data on the wood density and chemical properties of second-growth Douglas-fir from Vancouver Island.

Materials and Methods

Tree and Sample Selection

From each site three trees were selected, one each of low, medium and high density, based on field determinations of wood density using breast height disks or increment cores. Using the latter gave density values about 6 percent higher than those from disks, but was more convenient. A large range of wood density was sought so as to derive meaningful relationships between wood density and other wood and pulp properties. These trees formed a part of each 10 tree set chosen by Forintek Canada Corp. for their comparison study of basic wood properties. Trees from only three sites, Ladysmith, Lizard Lake and Jordan River, were evaluated.

Juvenile wood was defined as the innermost region of 20 annual rings: the inner cylinder of wood that surrounds the pith from the base to the top of the stemwood.

From each tree, three samples, juvenile wood and mature wood from the butt and top wood, were taken according to the schematic shown in Figure 10-1. Two adjacent 1 meter long bolts were taken from the butt, and two adjacent 1.5 meter long bolts were removed near the 80 percent total height position, at which the annual rings varied from 17 to 23. These top wood samples were mostly juvenile wood,

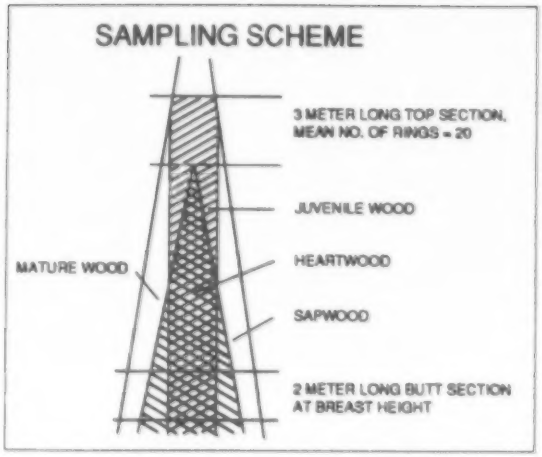


Fig. 10-1 Sampling plan for juvenile, mature and t

contained heartwood in the first 8 to 10 annual rings, and served as an internal check on the juvenile wood from the breast height bolts which were all heartwood. Top wood samples represent, but are not identical to, material typical of thinnings of a similar age.

The ends of each bolt were painted with a PVA glue to prevent moisture loss. The bolts were then transported to the Vancouver laboratory and stored frozen until processed.

Two 2.5 centimeter thick disks for the determination of wood properties were taken between each pair of butt bolts and each pair of top wood bolts within an hour of felling, and were double-bagged and frozen until used.

Determination of Moisture Content and Density

Moisture content was determined by drying at 105°C one of the two disks cut from butt and top sections; moisture retained in the sealed bags was accounted for.

Each disk not used for moisture determination was cut into an even number of pie slices and opposite segments (common diameter) were used for wood density determinations by means of a modified, on-the-balance procedure according to TAPPI Standard T18 m-53. Density determinations on chips, prepared as described later, were done using a modification of TAPPI Standard T258 om-85.

Determination of Chemical Properties

Chemical properties were determined from the remaining (opposite) pie segments from butt disks which were separated into juvenile wood (first 20 annual rings from pith) and mature wood (ring 21 to cambium). Segments from the top disks were used without separation.

Samples of butt juvenile wood, butt mature wood and top wood were cut into matchstick size pieces and comminuted in

a Wiley mill to pass a 40-mesh screen. All three ground wood samples from each tree were subjected successively to alcohol/benzene, alcohol and hot water extractions according to TAPPI Standards T204 os-76, T264 om-82 and T207 om-81, respectively.

Ground wood samples after the three successive extractions were used for Klason lignin determinations according to TAPPI Standard T222 om-83.

A one-percent caustic solubility was done on an aliquot of each untreated ground wood sample according to TAPPI Standard T212 om-83.

One aliquot of each untreated ground wood sample was extracted with alcohol, the solvent was removed under reduced pressure and the resulting extract taken up in alcohol (2 milliliters). This extract was analyzed for dihydroquercetin (DHQ) by HPLC using a 75 percent 0.2M $NH_4H_2PO_4$, 25 percent methanol eluent on a Spherisorb 0DS-1 column, according to an unpublished method developed by Forintek Canada Corp., Western Laboratory.

One aliquot (50 milliliters) of filtrate from the Klason lignin determinations from each wood sample was neutralized (pH 7) using NaOH solution. The neutralized aliquot was freeze-dried and the solid mixture analyzed by GLC; the sugars were determined as their alditol acetates.

Statistical Analysis

Wood density and chemical properties of juvenile wood, mature wood and top wood were compared using 14 different ANOVA models of the form:

$$Y_{ij} = M + T_i + P_j + eij\ ;\ i = 1, 2 \ldots\ldots 9;\ j = 1,2,3.$$

where:

- Y_{ij} = the value of the property for the i^{th} tree and j^{th} position in the stem.
- M = overall mean of the property.
- T_i = effect on Y due to the i^{th} tree.
- P_j = effect on Y due to position (juvenile wood, mature wood, top wood).
- eij = random variation. The eij's are assumed to be normally distributed with mean zero and constant variance.

This model is appropriate because differences in property values between positions within trees are of interest rather than differences between trees. Orthogonal contrasts for mature wood against the other two positions, and for juvenile wood against top wood were used to explore significant position effects.

Chip Preparation

Debarked sections of juvenile wood, mature wood and top wood (Figure 10-1) were chipped in a CAE 6-knife disk chipper to provide chips for chemical and mechanical pulping trials. Each of the 27 chip samples (3 sites x 3 trees x 3 tree components) was screened to remove oversize and fine material, and well mixed before representative samples were taken.

Results And Discussion

Wood Characteristics of Second-Growth Douglas-Fir

The physical and chemical characteristics of the 27 samples of wood and chips that comprise the test material in this study are provided in Tables 10-1 to 10-3.

Table 10-1. Wood Characteristics of Second-Growth Douglas-Fir

Tree No.	Wood Sample	Wood Density kg/m³		Disk Moisture Content, % Green Wood	Average Radius JW[1] at BH[4] cm	Age BH[4] Years
		Disk	Chips			
			Ladysmith			
7	JW[1]	427	435	26.3	11.4	52
	MW[2]	530	508	42.1		
	TW[3]	396	385	54.2		
2	JW[1]	395	388	26.3	12.7	50
	MW[2]	450	441	46.5		
	TW[3]	415	408	54.2		
9	JW[1]	360	346	26.9	10.2	59
	MW[2]	410	396	45.2		
	TW[3]	390	389	54.0		
			Lizard Lake			
9	JW[1]	490	487	26.9	17.1	52
	MW[2]	521	512	40.3		
	TW[3]	439	415	49.1		
7	JW[1]	418	408	28.0	16.5	45
	MW[2]	481	456	45.6		
	TW[3]	387	384	56.7		
5	JW[1]	353	371	27.7	12.1	49
	MW[2]	398	399	49.8		
	TW[3]	319	325	61.3		
			Jordan River			
6	JW[1]	450	448	26.7	13.3	49
	MW[2]	558	534	38.5		
	TW[3]	396	406	55.8		
2	JW[1]	440	434	27.5	15.2	58
	MW[2]	485	478	49.4		
	TW[3]	410	397	54.7		
8	JW[1]	367	373	27.0	15.2	58
	MW[2]	423	424	46.4		
	TW[3]	382	386	57.0		

1. Butt juvenile wood (1st 20 annual rings)
2. Butt mature wood (Rings 21-45+)
3. Top wood (Average age: 20 years)
4. Breast height

Table 10-2. Extractives Contents and Caustic Solubility of Second-Growth Douglas-Fir

Tree No.	Wood Sample	Alcohol/ Benzene	Alcohol	Hot Water	Total	1% NaOH Solubility	DHQ[1]
		% od Wood					
		Ladysmith					
7	JW	2.9	0.7	4.0	7.6	16.0	0.94
	MW[2]	2.9	0.6	3.6	7.1	15.3	0.90
	TW[3]	2.1	0.4	3.2	5.7	14.9	0.23
2	JW	3.8	0.6	3.8	8.2	16.7	1.24
	MW[2]	3.4	0.5	3.7	7.6	15.5	1.36
	TW[3]	2.3	0.3	3.2	5.8	14.6	0.64
9	JW	3.3	0.7	4.6	8.6	17.6	0.72
	MW[2]	3.3	0.7	3.7	7.7	15.8	0.83
	TW[3]	1.9	0.4	2.8	5.1	14.4	0.68
		Lizard Lake					
9	JW	3.4	1.1	3.2	7.7	17.8	1.81
	MW[2]	3.0	0.6	3.3	6.9	16.2	1.71
	TW[3]	3.1	0.4	3.3	6.8	16.0	1.67
7	JW	3.8	0.8	3.9	8.5	17.6	2.29
	MW[2]	3.0	0.5	3.5	7.0	15.8	1.11
	TW[3]	2.3	0.5	3.9	6.7	16.0	0.39
5	JW	5.0	0.8	4.4	10.2	19.1	2.08
	MW[2]	2.6	0.6	3.3	6.5	15.0	1.34
	TW[3]	2.2	0.4	3.9	6.5	15.1	0.99
		Jordan River					
6	JW	4.5	1.0	2.9	8.4	17.3	2.82
	MW[2]	3.6	0.7	3.4	7.7	15.8	1.10
	TW[3]	2.3	0.6	2.9	5.8	15.4	0.97
2	JW	4.1	1.2	4.5	9.8	19.4	1.94
	MW[2]	3.0	0.7	3.8	7.5	17.0	1.20
	TW[3]	2.3	0.6	3.6	6.5	15.8	0.94
8	JW	3.8	0.7	4.7	9.2	18.2	2.01
	MW[2]	4.1	0.6	4.2	8.9	17.0	1.90
	TW[3]	2.5	0.7	3.6	6.8	16.1	0.90

1. Dihydroquercetin.
2. MW samples were slower to filter than JW samples during hot water and 1% NaOH extractions and usually required a coarse filter instead of a medium one.
3. TW samples required a coarse filter for hot water and 1% NaOH extractions because of the slower washing stage; after hot water extractions, drying times were much longer for TW than for either JW or MW.

Table 10-3. Klason Lignin and Sugar Contents of Second-Growth Douglas-Fir

Tree No.	Wood Sample	Klason Lignin	Arabinose	Xylose	Mannose	Galactose	Glucose
		% extractive-free od Wood					
		Ladysmith					
7	JW	27.6	0.5	4.1	16.1	2.0	49.9
	MW	26.1	1.0	3.3	16.8	2.1	50.8
	TW	26.9	1.6	5.0	15.8	3.7	47.1
2	JW	30.2	0.6	4.8	14.8	2.5	47.0
	MW	28.6	0.9	3.8	14.5	2.7	49.6
	TW	27.7	1.2	5.7	14.5	3.5	47.1
9	JW	31.8	0.5	5.0	13.0	2.9	46.9
	MW	28.8	1.0	3.9	15.0	2.6	48.8
	TW	29.1	1.6	5.9	12.8	4.3	46.4
		Lizard Lake					
9	JW	29.0	0.9	4.1	17.0	2.6	46.6
	MW	27.5	0.9	3.3	17.0	2.1	49.3
	TW	27.1	1.5	5.0	16.1	3.3	46.9
7	JW	28.4	0.7	4.4	16.4	2.2	47.7
	MW	26.6	1.1	3.4	17.2	2.1	49.4
	TW	25.8	1.5	4.8	16.2	2.9	48.8
5	JW	29.4	0.9	3.9	16.3	2.8	46.5
	MW	27.7	1.2	3.3	16.1	2.3	49.3
	TW	26.6	1.5	4.9	15.7	2.9	48.3
		Jordan River					
6	JW	29.6	0.6	4.4	14.9	2.0	48.7
	MW	27.1	0.9	3.4	16.3	2.0	50.2
	TW	26.5	1.2	4.9	15.1	3.2	49.0
2	JW	30.6	0.6	4.4	14.6	3.1	46.7
	MW	27.6	0.9	3.8	15.8	2.2	49.8
	TW	27.0	1.5	4.9	17.0	3.6	46.0
8	JW	30.3	0.4	4.4	14.6	2.1	48.2
	MW	28.1	0.9	3.7	15.7	2.1	49.5
	TW	27.1	1.5	5.2	15.8	3.5	46.9

Basic densities of disks and chips, and disk moisture contents are shown in Table 10-1 for three trees each from Ladysmith, Lizard Lake and Jordan River sites, respectively.

There were large differences in wood density between trees, and between the juvenile wood and mature wood of each tree. Trees with the highest and lowest densities selected from each site were representative of the density range found for coastal Douglas-fir (see Chapter 1). The wood density of juvenile wood was consistently lower than that of mature wood from a given tree by amounts ranging from a low of 6 percent to a high of 19 percent, with a mean value of 13 percent for all nine trees.

However, the juvenile wood density of the highest density tree on a site was always higher than the mature wood density of the lowest density tree from the same site (see Figure 1-5). This observation has enormous implications for the planning of Canada's future managed resource.

In a natural stand, wood density is normally distributed so that some trees will have profiles displaced upwards or downwards

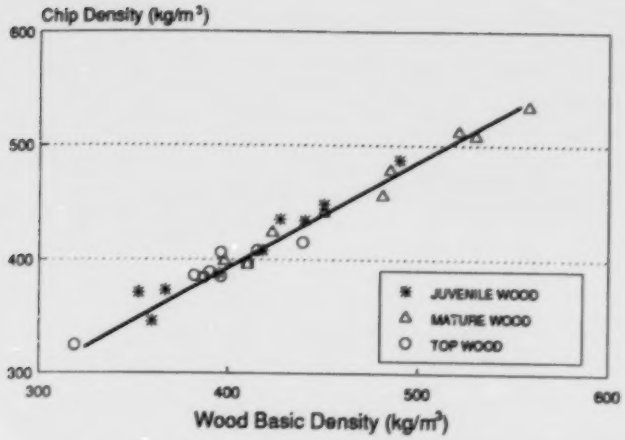


Fig 10-2 Chip density versus basic wood density and fitted regression model

Table 10-4. Results of Orthogonal Contrasts for Wood Density and Chemical Properties of Second-Growth Douglas-Fir

Property	Ordering of Property Values within Trees by Position (Significant at 5% Level)					
Wood density	JW[1]	,	TW[2]	<	MW[3]	
Alcohol/benzene extractives	JW	>	MW	>	TW	
Alcohol extractives	JW	>	MW	>	TW	
Hot water extractives	JW	,	MW	>	TW	
Total extractives	JW	>	MW	>	TW	
1% NaOH solubility	JW	>	MW	,	TW	
Dihydroquercetin	JW	>	MW	,	TW	
Klason lignin	JW	>	MW	,	TW	
Arabinose	JW	<	MW	<	TW	
Xylose	MW	<	JW	<	TW	
Mannose	MW	,	JW	,	TW	(no difference)
Galactose	TW	>	JW	,	MW	
Glucose	MW	>	JW	,	TW	
Total Sugars	JW	<	MW	,	TW	

1. Juvenile wood
2. Top wood
3. Mature wood

from an average value. By selecting the highest density trees as seed sources, the probability is good that the future resource will have juvenile wood densities that are higher than that in today's stands. By so doing it may be possible to at least maintain the present average wood density in the future fast-grown Douglas-fir resource.

Basic densities of disks and chips are plotted in Figure 10-2 for all 27 wood samples. Not surprisingly, the densities of disks and chips are highly correlated, $r^2 = 0.97$, confirming earlier work by Kibblewhite (1980) on *Pinus radiata*. The regression equation is:

Density (chips) = 43.5 + 0.884 [Density (disks)]

This line crosses the line Density (chips) = Density (disks) at 375 kilograms per cubic meter.

Therefore, densities determined from thin disk samples were found to increasingly underestimate chip densities above 375 kilograms per cubic meter. However, these differences are relatively small and we conclude that densities determined from thin disk samples are representative of chips produced from 2 meter long butt or 3 meter long top wood sections. Disk densities ranged from 319 to 558 kilograms per cubic meter compared with the corresponding range from chips of 325 to 534 kilograms per cubic meter.

Moisture contents of juvenile wood samples were consistently and substantially lower than those of mature wood and top wood and were at or below the fiber saturation point. The values for juvenile wood were entirely consistent with those previously observed for heartwoods of mature Douglas-fir and other softwoods (Haygreen and Bowyer, 1982). This could lead to problems with liquor penetration in chemical pulping in mills not equipped with adequate atmospheric presteaming facilities. In refiner mechanical pulping operations, chip washing and/or presteaming should serve to overcome any problems due to moisture deficiencies. Moisture contents of top wood samples were consistently higher than those of mature wood.

Extractives Contents and One-Percent Caustic Solubility of Second-Growth Douglas-Fir

Extractives contents and caustic solubilities determined on disks from trees from Ladysmith, Lizard Lake and Jordan River are shown in Table 10-2.

Total extractives ranged from 5.1 to 10.2 percent with the smallest portion found in the alcohol phase. One-percent caustic solubilities ranged from 14.4 to 19.4 percent. Total extractives and caustic solubilities increased consistently in the order, top wood ≤ mature wood < juvenile wood, as shown in Table 10-4, and are plotted in Figure 10-3 for all 27 samples. The good correlation ($r^2 = 0.83$) shows the strong dependency of caustic solubility on extractives content and provides useful data for chemical pulping studies from the viewpoints of pulp yield and alkali consumption. The regression equation is:

1% NaOH (disks) = 9.36 + 0.94 [Extractives (disks)]

Data on extractives contents and one-percent caustic solubility of old-growth Douglas-fir are sparse, but are not inconsistent with those found here for mature wood samples (Bray, *et al.*, 1940; Martin, 1949). Extractives contents in the juvenile wood of all nine trees (range 7.6 to 10.2 percent) were higher

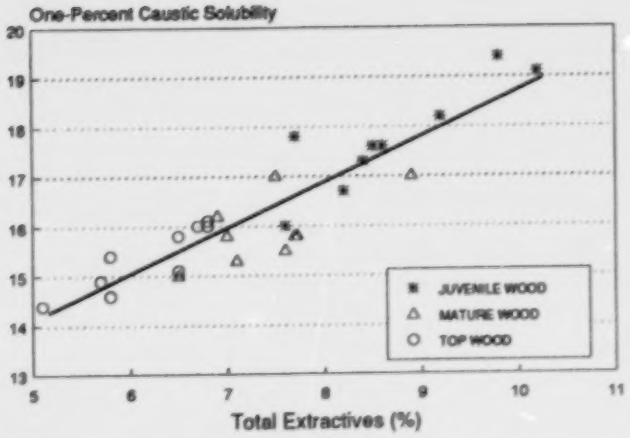


Fig. 10-3 One-percent caustic solubility versus total extractive content and fitted regression model

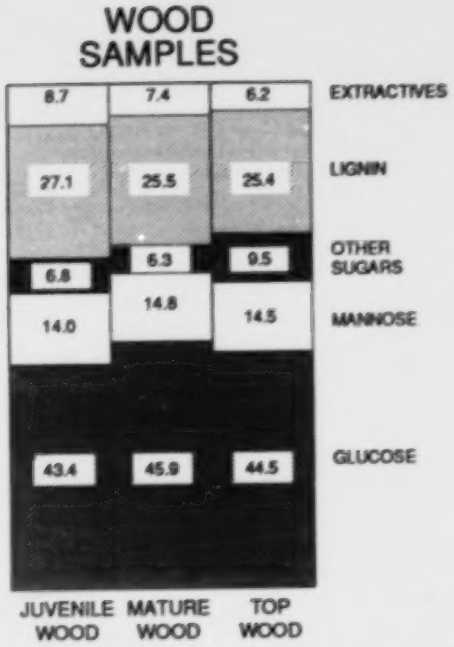


Fig. 10-4 Average chemical component contents for juvenile, mature and top wood

than those in the top wood samples (range 5.1 to 6.8 percent). This finding reflects the greater heartwood content in the former of the two types of juvenile wood.

DHQ is a polyphenol that contributes to the low brightness, high brightness reversion and poor response to peroxide bleaching of Douglas-fir mechanical pulps (Hillis and Swain, 1962; Bublitz and Meng, 1974; Betz and Styan, 1974). Contents of DHQ are shown in Table 10-2. With two exceptions, DHQ contents increased in the order, top wood ≤ mature wood < juvenile wood, with average values of 0.82, 1.27 and 1.76 percent, respectively (Table 10-4). This trend follows the same order as for total extractives and caustic solubilities.

Klason Lignins of Second-Growth Douglas-Fir

Lignin contents of trees from three sites are shown in Table 10-3, based on extractive-free od wood. With two exceptions, Klason lignin contents increased in the order, top wood ≤ mature wood < juvenile wood (Table 10-4), with average values of 27.1, 27.6 and 29.7 percent, respectively. Thus, kraft pulp yields from these components could decrease in the same order if pulped to a constant lignin content (see Chapter 11).

Sugar Contents of Second-Growth Douglas-Fir

Contents of the five sugars, arabinose, xylose, mannose, galactose and glucose from nine trees are shown in Table 10-3, based on extractive-free od wood, and are summarized by tree component based on od wood in Figure 10-4. Differences between the juvenile wood, mature wood and top wood tree components were significant at the 5 percent level for each sugar (except mannose) and total sugars, Table 10-4. The lower carbohydrate and higher lignin contents of juvenile wood relative to mature wood result in lower kraft pulp yields for the former (see Chapter 11).

Conclusions

The basic density and wood chemistry of butt juvenile, butt mature wood and top wood samples have been determined from second-growth Douglas-fir trees of low, medium and high density from three different sites on Vancouver Island. Evaluations were performed on representative samples of disks cut from each tree and were repeated for density on chips prepared from each tree component for associated chemical and mechanical pulping studies.

The principal conclusions are as follows:

1. There were large differences in wood density between trees and between the juvenile wood and mature wood of each tree. The density of juvenile wood was consistently lower than that of mature wood from a given tree. Basic densities of disk and corresponding chip samples were highly correlated although disk densities do underestimate chip densities by small amounts above 375 kilograms per cubic meter.
2. Moisture contents of juvenile wood samples were consistently and substantially lower than those of mature wood and top wood and were at or below the fiber

saturation point. Moisture contents of top wood samples were consistently higher than those of mature wood.

3. Total extractives contents and one-percent caustic solubilities increased in the order, top wood ≤ mature wood < juvenile wood. Extractives contents in the juvenile wood of all trees were consistently higher than those in top wood samples because of the greater heartwood content in the butt portion of each tree. Total extractives contents and one-percent caustic solubilities were well correlated.

4. Klason lignin contents increased in the order, top wood = mature wood < juvenile wood.

5. Individual sugar and total sugar contents showed highly statistically significant differences for juvenile wood, mature wood and top wood.

The body of data presented here will be interpreted in the following two chapters on chemical and mechanical pulping, and pulp properties.

Acknowledgements

The authors gratefully acknowledge the valuable technical assistance of Phil Allen, Resource Evaluation Section, Vancouver Laboratory, who carried out many of the evaluations described herein, and to Wai Gee, Surjit Johal, Barry Christie and James Drummond who also assisted in sample procurement, sample preparation or sample evaluation.

The assistance of Emil Koller and Maurice Douek, Pointe Claire Laboratory, for ANOVA calculations and sugar analyses, respectively, is much appreciated as are the efforts of Jean Cook, Forintek Canada Corp., Western Laboratory, who reworked much of the original statistical data.

References

Betz, R.G. and G.E. Styan. 1974. Brightening of Douglas-fir groundwood. Pulp Pap. Mag. Can. 75(C):111-114.

Bonnor, G.M. 1982. Canada's forest inventory 1981. For. Stat. Systems Branch, Can. For. Serv., Dep. Environ., Chalk River, ON., 79p.

Bray, M.W., S.L. Schwartz, and J.S. Martin. 1940. Sulphate pulping of Douglas-fir. Tech. Assoc. Papers 23:232-238.

Bublitz, W.J. 1971. Kraft pulping quality of thinnings from young Douglas-fir. Tappi 54(6):928-932.

Bublitz, W.J. and S.N. Chia. 1974. Seedling characteristics and kraft pulping properties of young Douglas-fir. For. Prod. J. 24(3):48-52.

Bublitz, W.J. and T.Y. Meng. 1974. The effect of certain flavonoids on the bleaching of Douglas-fir refiner groundwood. Pulp Pap. Mag. Can. 75(3):85-90.

Corson, S.R. and F.M. Lim. 1983. Physical characteristics of thermomechanical pulp from young radiata pine. Appita 37(1):35-40.

Erickson, H.D. and T. Arima. 1974. Douglas-fir wood quality studies (2). Effects of age and stimulated growth on fibril angle and chemical constituents. Wood Sci. and Tech. 8(4):255-265.

Hatton, J.V. and J.L. Keays. 1972. Complete-tree-utilization studies. III. Yield and quality of kraft pulp from the components of *Pseudotsuga menziesii*. Tappi 55(10):1505-1508.

Haygreen, J.G. and J.L. Bowyer. 1982. Forest products and wood science - an introduction. Ames, Iowa: Iowa State Univ. Press, p.170.

Hillis, W.E. and T. Swain. 1962. The influence of extractives on the color of groundwood and newsprint, Chapter 12. In: Wood Extractives and Their Significance to the Pulp and Paper Industries. W.E. Hillis, ed. Academic Press, New York, p.405-419.

Ifju, G. and R.W. Kennedy. 1962. Some variables affecting microtensile strength of Douglas-fir. For. Prod. J. 12(5):213-217.

Kibblewhite, R.P. 1980. Radiata pine corewood and slabwood, and their interrelationships with (kraft) pulp and handsheet properties. New Zealand J. For. Sci. 10(3):533-550.

Kibblewhite, R.P. 1982. Qualities of radiata pine papermaking fibres. Appita 35(4):289-298.

Kibblewhite, R.P. 1984a. Fibres and fines of some radiata pine corewood and slabwood thermomechanical and refiner mechanical pulps. Appita 37(8):650-657.

Kibblewhite, R.P. 1984b. Radiata pine wood and kraft pulp quality relationships. Appita 37(9):741-747.

Martin, J.S. 1949. Sulphate pulping of logging and sawmill wastes of old-growth Douglas-fir and of certain associated species. Tappi 32(12):534-539.

North Carolina State University. 1984. Proc. of Symp. Utilization of the changing wood resource in the southern United States, N.C. State Univ., School of Forest Resources, N.C. Agric. Exten. Serv., Div. Lifelong Educ., June 12-14.

Uprichard, J.M. 1980. Effects of wood age on papermaking properties of radiata pine kraft pulps. New Zealand J. For. Sci. 10(3):558-576.

Wardrop, A.B. 1951. Cell wall organization and the properties of the xylem. I. Cell wall organization and the variation of breaking load in tension of the xylem in conifer stems. Aust. J. Sci. Res. Series B 4(4):391-414.

CHAPTER 11

Unbleached Kraft Pulps

J.V. Hatton and K. Hunt *Resource Evaluation Section, Pulp and Paper Research Institute of Canada*

Introduction

As shown in previous chapters, the physical properties of juvenile wood differ from those of mature wood, and chemical characteristics such as extractives and lignin contents are higher in juvenile wood. Many of these differences may be undesirable for processing and end use requirements. This Chapter presents corresponding data on the pulping characteristics, yield, and physical properties of unbleached kraft pulps made from the same samples as used for the study reported in Chapter 10 and discusses significant relationships between density, fiber and kraft pulp handsheet properties.

Materials and Methods

Chip Preparation

After thawing the samples, butt and top wood bolts were debarked and butt bolts were slabbed on a bandsaw to produce juvenile wood and mature wood sections. These sections of juvenile wood, mature wood and top wood were chipped in a CAE 6-knife disk chipper to provide chips for mechanical and kraft pulping trials. Each of the 27 chip samples (3 sites x 3 trees x 3 components) was screened to remove oversize and fine material and was homogenized before representative samples were taken.

Kraft Pulping

Three series of kraft cooks were made as follows.

First Series

Six representative aliquots of accept chips from each of the 27 samples available were cooked in bombs (50 gram od charges) within a precision digester assemble (Keays and Bagley, 1970) to produce kraft pulps with Klason lignin contents in the range 4 to 18 percent, od pulp basis. Accept chips were those that passed one and one-eighth inch holes on a shaker screen, but were retained on three-sixteenth inch holes; all accept chips had thicknesses in the range from 2 to 6 millimetres. The following kraft cooking conditions were used:

Time-to-maximum temperature, min.	:	135
Maximum cooking temperature, °C	:	170
H factor	:	300 to 2100
Effective alkali (EA), % od wood	:	16.0
Sulphidity, %	:	25.0
Liquor-to-wood ratio	:	4.5:1

Each pulp was washed and processed according to standard procedures. The residual effective alkali (EA_{res}) of each black liquor was determined by barium carbonate precipitation and potentiometric titration with hydrochloric acid to pH 8.3, as recommended by Kesler (1966).

Thus, 27 x 6 or 162 measurements of pulp yield, H factor and EA_{res} were made. For all 27 samples, regression lines were fitted through each six-cook set to give 27 x 3 or 81 regression equations from which pulp yield, H factor and effective alkali consumed were estimated at Klason lignin contents of 5 and 15 percent, od pulp.

Second Series

For the purpose of producing large quantities of unbleached kraft pulps with Klason lignin contents at approximately 5 percent, i.e., representative of bleachable grades, a further 27 samples each of 4.0 kilograms od wood were individually cooked in a one cubic foot Weverk laboratory digester. Cooking conditions were based on data produced in the first series of cooks. All pulps were washed, screened and processed as stated above.

Third Series

A new technique, which will be reported separately, was developed for the purpose of cooking a large number of 5 gram od basis wood samples to Kappa numbers in the range 35 to 40. A total of more than 400 individual samples taken from the test trees at different locations along each stem from base to crown, and from pith-to-bark, were cooked by the kraft process to provide pulp samples for analysis of fiber length.

Fiber Properties

Representative samples of more than 20,000 fibers from each of the 27 large scale bleachable-grade kraft cooks (second series) were analyzed for fiber length and coarseness using a Kajaani FS-100 instrument. The >400 miniature kraft pulp samples were similarly analyzed for fiber length in conjunction with Forintek Canada Corp. and appropriate data were used to plot fiber length distributions from pith-to-bark for butt and top wood sections of the nine trees sampled. These data are described in detail in Chapter 4.

Handsheet Properties

Four representative samples of each of the 27 bleachable-grade kraft pulps (second series) were beaten in a PFI mill for 0; 3000; 6000; and 12000 revolutions. Handsheets were made and tested for structural, mechanical and optical properties using standard methods, to give 27 x 4, or 108 sets of data for analysis.

Statistical Analysis

The effects of wood and fiber properties on the bulk, strength and optical properties of handsheets can be determined on kraft pulps which have been lightly, moderately or well beaten. In this Chapter, sheet properties were examined for pulps which had been refined for 1000 revolutions in a PFI mill, i.e., lightly beaten. This basis of comparison was considered to be the most meaningful because, as recommended by Kibblewhite (1980), it allows all pulps to be subjected to a limited, but similar, amount of mechanical treatment before sheetmaking.

The 27 bleachable-grade kraft pulps had been beaten for 3000, 6000 and 12000 revolutions in a PFI mill. Therefore, to bring the strength properties of each pulp to a baseline of 1000 revolutions, the following two-step procedure was followed, as earlier proposed by Hatton and Samkova (1972) based on a suggestion by Clark (1970).

- Regression equations of sheet density against $\log_{10}$ (PFI revolutions +1) were calculated and sheet density values equivalent to 1000 revolutions in a PFI mill were interpolated (Hatton and Samkova, 1972). The coefficients of determination (r^2) for all 27 regression equations were 0.97 or better.

- Regression equations were calculated for each selected strength property against sheet density at 0, 3000, 6000 and 12000 revolutions. From these 108 regression equations the values of individual strength properties were derived by inserting the appropriate sheet density value at 1000 revolutions determined as described in the above first step. The coefficients of determination for 98 of these regression equations were 0.95 or better, and those for the remainder were between 0.84 and 0.95. It should be noted that values of tear index at 1000 revolutions derived in this manner were entirely reliable since the corresponding values of sheet density for all 27 pulps were such that each tear index had just passed through its maximum value.

Following this procedure, multiple linear regression analysis was carried out using the five handsheet properties of sheet density, tensile index, stretch, burst index and tear index as dependent variables, and the five wood and fiber properties of disk density, chip density, weight-weighted fiber length, fiber coarseness and R14 fraction as independent variables. The objective of this analysis was to develop prediction equations for bulk and strength properties of kraft pulp handsheets with measured fiber characteristics produced from wood of a given density.

The means, standard deviations, minima and maxima of the 27 values for each variable were computed because prediction equations developed from these data are not valid for future values of the independent variables outside the range of these data.

The Pearson correlation coefficient was computed for each pair of variables and tests for significant linear correlation were performed. These tests are useful for pairs of dependent variables because significant linear correlations between any two variables (i.e., $r \geq 0.99$) could allow one handsheet property to be determined from another. They are useful for pairs of independent variables because significant linear correlations between any two variables, one of which is included in a prediction equation, would suggest that inclusion of the other variable in the equations would be unlikely to produce an equation with improved predictive power.

Linear prediction equations for each dependent variable were developed using the available independent variables. In each case, the "best" one, two and three independent variable models were first computed. "Best" was defined as that combination of independent variables which gave the highest R^2 for a given number of independent variables. Whenever an additional variable was added to the equation an F-test was performed to determine whether the new variable added significantly to the regression (Weisberg, 1980). Finally, the predicted values versus observed values for the chosen predictive models were plotted for each dependent variable.

Results and Discussion

Kraft Cooking of Juvenile Wood, Mature Wood and Top Wood Components

Pulp yields at 5 percent (bleachable-grade) and 15 percent (linerboard-grade) Klason lignin for all juvenile wood, mature wood and top wood components estimated from data obtained in the first series of cooks are shown in Table 11-1, together with their corresponding H factors and effective alkali consumptions.

Bleachable-Grade Pulps

For each tree, yields from juvenile wood were always lower than those from their corresponding mature wood component. Differences ranged from a low of 0.9 to a high of 2.8 percent, with a mean of 1.65 percent od wood. Yields from the top wood component of each tree were higher than those from the corresponding juvenile wood component. Mean and standard deviation values of pulp yield for each nine sample composite set of juvenile wood, mature wood and top wood components were 45.6 (1.0), 47.2 (0.9) and 47.6 (1.0) percent od wood, respectively.

Table 11-1. Kraft Cooking of Second-Growth Douglas-Fir to Bleachable and Linerboard Grades

Tree No.	Wood Sample	Chip Density kg/m³	At 5% Klason Lignin, od Pulp (Bleachable Grade)			At 15% Klason Lignin, od Pulp (Linerboard Grade)		
			Pulp Yield % od Wood	H Factor	Effective Alkali Consumed % od Wood	Pulp Yield % od Wood	H Factor	Effective Alkali Consumed % od Wood
				Ladysmith				
7	JW[1]	435	48.2	1310	11.0	57.0	380	9.6
	MW[2]	508	49.2	1440	10.9	58.6	450	9.4
	TW[3]	385	48.2	1480	11.1	57.7	430	9.6
2	JW[1]	388	46.0	1290	11.5	54.9	385	10.0
	MW[2]	441	47.2	1510	11.1	56.4	470	9.7
	TW[3]	408	46.5	1450	11.3	55.7	440	9.7
9	JW[1]	346	45.0	1300	11.4	53.5	410	9.8
	MW[2]	396	45.9	1610	11.3	54.8	540	9.7
	TW[3]	389	45.3	1610	11.2	54.6	510	9.6
				Lizard Lake				
9	JW[1]	487	45.1	1680	11.4	53.4	500	9.9
	MW[2]	512	46.4	1970	11.5	55.3	630	9.8
	TW[3]	415	47.9	1515	11.3	57.5	490	9.8
7	JW[1]	408	46.0	1425	11.2	55.1	440	9.9
	MW[2]	456	47.5	1670	11.1	56.7	460	9.9
	TW[3]	384	48.4	1490	11.2	57.7	430	9.8
5	JW[1]	371	45.5	1290	11.1	54.4	410	9.7
	MW[2]	399	47.9	1320	10.8	57.4	410	9.3
	TW[3]	325	48.4	1280	10.5	58.1	375	9.1
				Jordan River				
6	JW[1]	448	44.6	1540	11.7	54.5	510	10.1
	MW[2]	534	47.4	1730	11.6	56.9	580	10.2
	TW[3]	406	48.3	1485	11.3	58.3	480	10.0
2	JW[1]	434	44.6	1540	11.7	53.4	470	10.1
	MW[2]	478	46.6	1570	11.5	56.4	560	9.9
	TW[3]	397	47.7	1520	11.2	56.8	470	9.7
8	JW[1]	373	45.4	1345	11.3	54.3	380	9.9
	MW[2]	424	46.6	1585	11.5	55.6	520	10.2
	TW[3]	386	47.3	1490	11.4	56.9	490	9.9

1. Butt juvenile wood (1st 20 annual rings)
2. Butt mature wood (Rings 21-45+)
3. Top wood (Average age: 20 years)

The H factors required to produce these pulps at 5 percent Klason lignin content were always smaller for a juvenile wood than for its corresponding mature wood component. Differences ranged from a low of 30 to a high of 310, with a mean of 190. H factors for top wood components were larger than for the juvenile wood but lower than for the mature wood components. Mean and standard deviation values of the H factors for each nine sample composite set of juvenile wood, mature wood and top wood components were 1415 (135), 1600 (175) and 1480 (80), respectively.

With two exceptions, more alkali was required to cook each juvenile wood component than its corresponding mature wood component from a given tree, but the differences were smaller than would have been anticipated from the plot of caustic solubility versus extractives content (Figure 10-3). Mean and standard deviation values of the effective alkali consumed for each nine sample composite set of juvenile wood, mature wood and top wood components were 11.37 (0.23), 11.26 (0.28) and 11.17 (0.25) percent od wood, respectively.

Thus, although pulp yields were lower for juvenile wood compared to their corresponding mature wood components by 1.65 percent od wood, juvenile wood cooked more rapidly (by 190 H factor units) and required only a nominal increase of 0.1 percent od wood in effective alkali consumed.

Linerboard-Grade Pulps

Similar trends were found for pulp yields, H factor requirements and effective alkali consumptions as for the bleachable-grade pulps. This is evident from the plots of linerboard-grade versus bleachable-grade pulp yields shown in Figure 11-1 and from the corresponding H factor and effective alkali consumption plots of Figures 11-2 and 11-3, respectively.

The three regression equations are shown below:

Pulp yield (15% KL), % od wood = 2.06 + 1.15 Pulp yield (5%KL); $r^2 = 0.95$

H factor (15% KL) = -78 + 0.37 H factor (5% KL); $r^2 = 0.82$

EA_{cons} (15% KL), % od wood = 0.20 + 0.85 EA_{cons} (5% KL); $r^2 = 0.81$

Relationships Between Pulp Yield and Klason Lignin

Values of A and B in the regression equation:

Pulp yield = A + B • Klason lignin (pulp)

for each of the 27 unbleached kraft pulps are shown in Table 11-2 based on data from the first series of cooks. In the Klason lignin range from 5 to 15 percent, yield and Klason lignin in pulp were highly correlated. The linear relationship between pulp yield and Klason lignin differed significantly with position in the stem as shown by the regression equations for juvenile wood, mature wood and top wood.

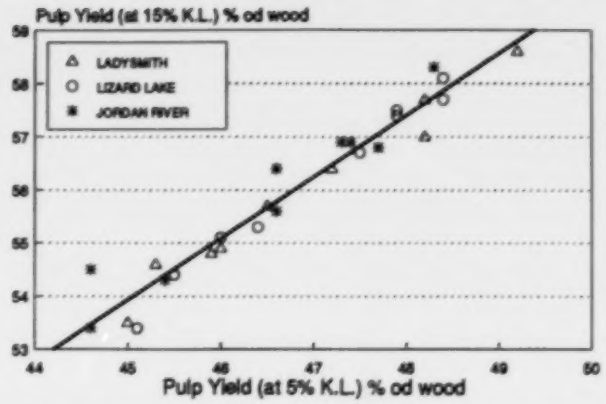


Fig. 11-1 Linerboard-grade pulp yield versus bleachable-grade pulp yield with the fitted linear model

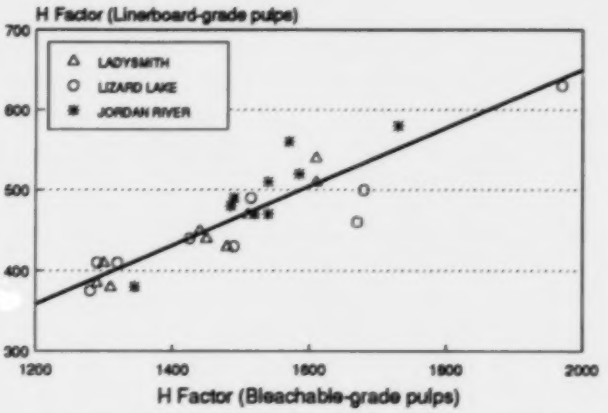


Fig. 11-2 Linerboard-grade H factor versus bleachable-grade H factor with the fitted linear model

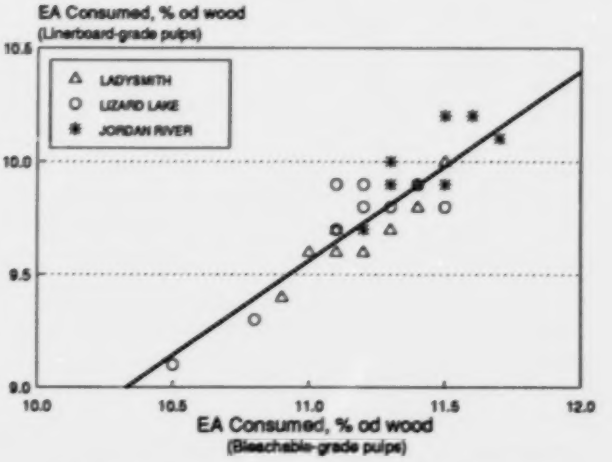


Fig. 11-3 Linerboard-grade effective alkali consumed versus bleachable-grade effective alkali consumed with the fitted linear model

Table 11-2. Values of A and B in the Equation: Pulp Yield = A + B • Klason Lignin (Pulp)[1]

Site	Tree No.	Wood Sample	A	B
Ladysmith	7	JW	43.8	0.88
		MW	44.5	0.94
		TW	43.4	0.96
	2	JW	41.6	0.89
		MW	42.5	0.93
		TW	41.9	0.93
	9	JW	40.7	0.85
		MW	41.4	0.90
		TW	40.7	0.93
Lizard Lake	9	JW	41.0	0.83
		MW	41.4	0.99
		TW	43.1	0.96
	7	JW	41.5	0.91
		MW	42.8	0.93
		TW	43.7	0.93
	5	JW	41.0	0.90
		MW	43.2	0.95
		TW	43.6	0.97
Jordan River	6	JW	39.7	0.99
		MW	42.6	0.96
		TW	43.2	1.01
	2	JW	40.2	0.88
		MW	41.7	0.98
		TW	43.2	0.90
	8	JW	40.9	0.90
		MW	42.0	0.91
		TW	42.5	0.96

1. Values of r^2 ranged from 0.99 to 1.00

Juvenile Wood

Pulp yield = 41.2 + 0.89 Klason lignin (pulp); $r^2 = 0.94$

Mature Wood

Pulp yield = 42.5 + 0.93 Klason lignin (pulp); $r^2 = 0.95$

Top Wood

Pulp yield = 43.0 + 0.93 Klason lignin (pulp); $r^2 = 0.94$

However, an analysis of covariance to test for homogeneity of slopes among position within a tree showed that three parallel lines could be fitted to the data with a common slope 0.92, and intercepts that were significantly different at the 5 percent level.

Pulp yields at 5 percent Klason lignin are plotted versus the wood lignin contents of the 27 chip samples in Figure 11-4.

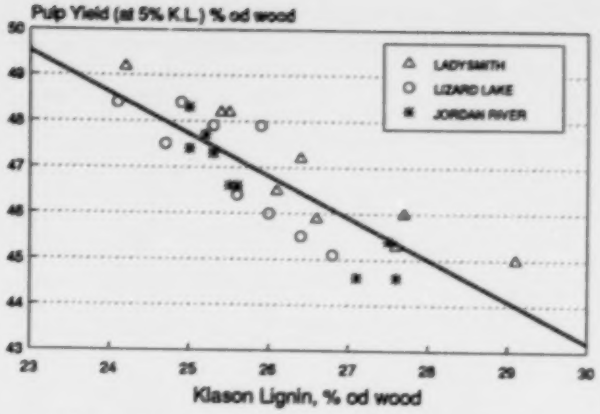


Fig. 11-4 Bleachable-grade kraft pulp yield versus wood Klason lignin content with the fitted linear model

Pulp yield decreased with increasing wood lignin content, but the relationships were different for each component as shown below. Yield and lignin content each covered a wide range of approximately 5 percent. The plot shows that as wood lignin content increases, our ability to predict pulp yield lessens. The regression equations for the three components both combined and separate are as follows:

All Components Combined

Pulp yield (5% KL), % od wood = 71.36 - 0.95 Wood lignin content; $r^2 = 0.72$

Juvenile Wood

Pulp yield (5% KL), % od wood = 63.19 - 0.65 Wood lignin content; $r^2 = 0.39$

Mature Wood

Pulp yield (5% KL), % od wood = 69.75 - 0.89 Wood lignin content; $r^2 = 0.49$

Top Wood

Pulp yield (5% KL), % od wood = 73.25 - 1.01 Wood lignin content; $r^2 = 0.87$

Relationships Between Residual Effective Alkali and H Factor

Over the range for which the plot of EA_{res} against log H is linear, EA_{res} and log H were highly correlated for each of the 27 bleachable-grade kraft pulps.

Values of A and B in the regression equation:

$$EA_{res} = A - B \cdot \log H$$

for juvenile wood, mature wood and top wood are shown below.

Juvenile Wood

EA_{res} = 13.11 - 2.67 log H; $r^2 = 0.92$

Table 11-3. Fiber Properties of Second-Growth Douglas-Fir

Site	Tree No.	Wood Sample	Fibre Coarseness µg/m	Weight-Weighted Fibre Length mm	R - 14 Fraction %
Ladysmith	7	JW	221	3.13	68.1
		MW	269	3.48	72.5
		TW	195	2.89	65.4
	2	JW	190	2.81	69.9
		MW	234	3.22	73.5
		TW	207	2.84	66.3
	9	JW	170	2.59	62.5
		MW	191	3.01	68.0
		TW	190	2.82	65.2
Lizard Lake	9	JW	200	2.39	31.0
		MW	233	3.08	53.7
		TW	232	2.62	36.7
	7	JW	220	2.74	49.2
		MW	224	3.37	66.1
		TW	221	2.80	49.9
	5	JW	223	2.87	54.0
		MW	247	3.31	63.8
		TW	248	2.88	51.4
Jordan River	6	JW	186	2.54	45.3
		MW	199	2.83	56.5
		TW	262	2.96	54.7
	2	JW	224	2.77	51.4
		MW	227	3.35	65.2
		TW	232	3.03	59.2
	8	JW	183	2.94	58.6
		MW	232	3.36	63.5
		TW	216	2.83	56.9

Mature Wood

$EA_{ms} = 13.64 - 2.76 \log H; \quad r^2 = 0.91$

Top Wood

$EA_{ms} = 14.28 - 2.98 \log H; \quad r^2 = 0.93$

However, an analysis of covariance showed no effect for component. Thus, the following combined regression equation can be used for all components which simplifies cook end point control.

$$EA_{ms} = 13.46 - 2.73 \log H; \quad r^2 = 0.89$$

Values of A did not follow those expected from previous work with softwood kraft pulps (Hatton, 1983) in which it was shown that, for a range of softwood kraft pulps, values of A should be close to the level of EA applied. The difference between the calculated intercept, 13.46 percent and the level of EA applied, 16.0 percent, is significant at the 5 percent level.

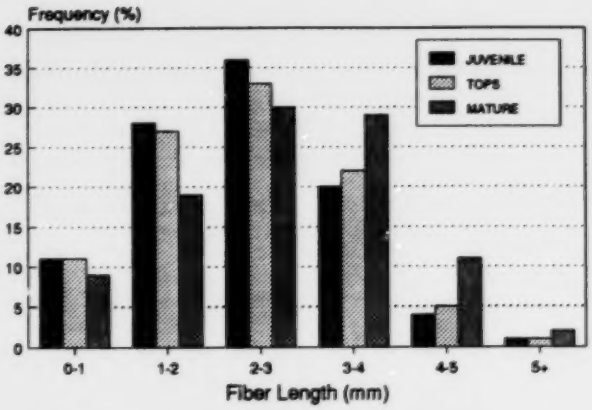


Fig. 11-5 Weight-weighted fiber length distributions of bleachable-grade kraft pulps from juvenile, mature and top wood

Fiber Properties

Fiber Coarseness

Values of fiber coarseness for the 27 bleachable-grade kraft pulps (second series) are shown in Table 11-3. They ranged from 170 to 269 micrograms per meter. For each of the nine trees, fibers from juvenile wood kraft pulps were consistently less coarse than those from the corresponding mature wood kraft pulps, although differences were relatively minor in some cases. The coarseness of fibers from top wood kraft pulps, however, did not fall into any well defined pattern vis-a-vis those from either juvenile wood or mature wood pulps from a given tree.

Therefore, kraft pulps from the juvenile wood section of the butt portion of each tree would be expected, because of their finer fibers, to exhibit increased interfiber bonding, leading to higher burst and tensile, but reduced tear, compared to pulps from the mature wood section of the butt portion of the same tree.

Fiber Length Distributions in Bleachable-Grade Kraft Pulps

Fiber length distributions of the 27 bleachable-grade kraft pulps from the second series of cooks were grouped by tree component as shown in Figure 11-5. Kraft pulps from juvenile wood and top wood samples had similar distribution frequencies whilst those from mature wood contained a higher proportion of long fibers. These trends are confirmed by the weight-weighted fiber length mean values of 2.75, 2.85 and 3.22 millimeters for juvenile wood, top wood and mature samples, respectively.

The pith-to-bark weighted fiber length of bleachable-grade kraft pulps determined by means of the miniature kraft cooks are shown in Figures 11-6 to 11-8 for butt samples from Ladysmith, Lizard Lake and Jordan River, respectively. The

Table 11-2. Values of A and B in the Equation: Pulp Yield = A + B • Klason Lignin (Pulp)[1]

Site	Tree No.	Wood Sample	A	B
Ladysmith	7	JW	43.8	0.88
		MW	44.5	0.94
		TW	43.4	0.96
	2	JW	41.6	0.89
		MW	42.5	0.93
		TW	41.9	0.93
	9	JW	40.7	0.85
		MW	41.4	0.90
		TW	40.7	0.93
Lizard Lake	9	JW	41.0	0.83
		MW	41.4	0.99
		TW	43.1	0.96
	7	JW	41.5	0.91
		MW	42.8	0.93
		TW	43.7	0.93
	5	JW	41.0	0.90
		MW	43.2	0.95
		TW	43.6	0.97
Jordan River	6	JW	39.7	0.99
		MW	42.6	0.96
		TW	43.2	1.01
	2	JW	40.2	0.88
		MW	41.7	0.98
		TW	43.2	0.90
	8	JW	40.9	0.90
		MW	42.0	0.91
		TW	42.5	0.96

1. Values of r^2 ranged from 0.99 to 1.00

Juvenile Wood

Pulp yield = 41.2 + 0.89 Klason lignin (pulp); $r^2 = 0.94$

Mature Wood

Pulp yield = 42.5 + 0.93 Klason lignin (pulp); $r^2 = 0.95$

Top Wood

Pulp yield = 43.0 + 0.93 Klason lignin (pulp); $r^2 = 0.94$

However, an analysis of covariance to test for homogeneity of slopes among position within a tree showed that three parallel lines could be fitted to the data with a common slope 0.92, and intercepts that were significantly different at the 5 percent level.

Pulp yields at 5 percent Klason lignin are plotted versus the wood lignin contents of the 27 chip samples in Figure 11-4.

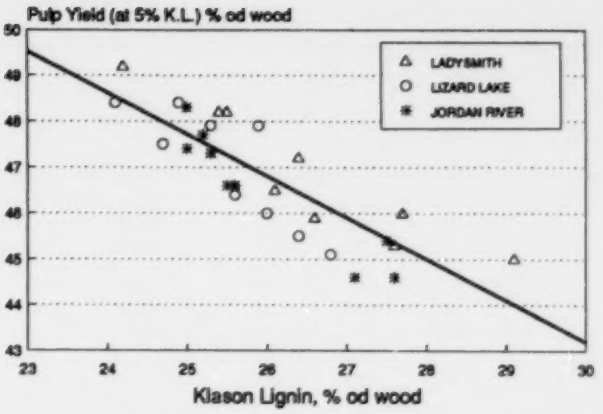


Fig. 11-4 Bleachable-grade kraft pulp yield versus wood Klason lignin content with the fitted linear model

Pulp yield decreased with increasing wood lignin content, but the relationships were different for each component as shown below. Yield and lignin content each covered a wide range of approximately 5 percent. The plot shows that as wood lignin content increases, our ability to predict pulp yield lessens. The regression equations for the three components both combined and separate are as follows:

All Components Combined

Pulp yield (5% KL), % od wood = 71.36 - 0.95 Wood lignin content; $r^2 = 0.72$

Juvenile Wood

Pulp yield (5% KL), % od wood = 63.19 - 0.65 Wood lignin content; $r^2 = 0.39$

Mature Wood

Pulp yield (5% KL), % od wood = 69.75 - 0.89 Wood lignin content; $r^2 = 0.49$

Top Wood

Pulp yield (5% KL), % od wood = 73.25 - 1.01 Wood lignin content; $r^2 = 0.87$

Relationships Between Residual Effective Alkali and H Factor

Over the range for which the plot of EA_{res} against log H is linear, EA_{res} and log H were highly correlated for each of the 27 bleachable-grade kraft pulps.

Values of A and B in the regression equation:

$$EA_{res} = A - B \cdot \log H$$

for juvenile wood, mature wood and top wood are shown below.

Juvenile Wood

EA_{res} = 13.11 - 2.67 log H; $r^2 = 0.92$

Table 11-3. Fiber Properties of Second-Growth Douglas-Fir

Site	Tree No.	Wood Sample	Fibre Coarseness µg/m	Weight-Weighted Fibre Length mm	R - 14 Fraction %
Ladysmith	7	JW	221	3.13	68.1
		MW	269	3.48	72.5
		TW	195	2.89	65.4
	2	JW	190	2.81	69.9
		MW	234	3.22	73.5
		TW	207	2.84	56.3
	9	JW	170	2.59	62.5
		MW	191	3.01	68.0
		TW	190	2.82	65.2
Lizard Lake	9	JW	200	2.39	31.0
		MW	233	3.08	53.7
		TW	232	2.62	36.7
	7	JW	220	2.74	49.2
		MW	224	3.37	66.1
		TW	221	2.80	49.9
	5	JW	223	2.87	54.0
		MW	247	3.31	63.8
		TW	248	2.88	51.4
Jordan River	6	JW	186	2.54	45.3
		MW	199	2.83	56.5
		TW	262	2.96	54.7
	2	JW	224	2.77	51.4
		MW	227	3.35	65.2
		TW	232	3.03	59.2
	8	JW	183	2.94	58.6
		MW	232	3.36	63.5
		TW	216	2.83	56.9

Mature Wood

$EA_{ms} = 13.64 - 2.76 \log H; \quad r^2 = 0.91$

Top Wood

$EA_{ms} = 14.28 - 2.98 \log H; \quad r^2 = 0.93$

However, an analysis of covariance showed no effect for component. Thus, the following combined regression equation can be used for all components which simplifies cook end point control.

$$EA_{ms} = 13.46 - 2.73 \log H; \quad r^2 = 0.89$$

Values of A did not follow those expected from previous work with softwood kraft pulps (Hatton, 1983) in which it was shown that, for a range of softwood kraft pulps, values of A should be close to the level of EA applied. The difference between the calculated intercept, 13.46 percent and the level of EA applied, 16.0 percent, is significant at the 5 percent level.

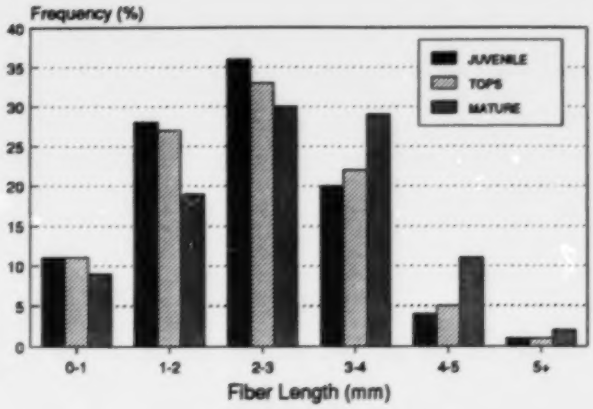


Fig. 11-5 Weight-weighted fiber length distributions of bleachable-grade kraft pulps from juvenile, mature and top wood

Fiber Properties

Fiber Coarseness

Values of fiber coarseness for the 27 bleachable-grade kraft pulps (second series) are shown in Table 11-3. They ranged from 170 to 269 micrograms per meter. For each of the nine trees, fibers from juvenile wood kraft pulps were consistently less coarse than those from the corresponding mature wood kraft pulps, although differences were relatively minor in some cases. The coarseness of fibers from top wood kraft pulps, however, did not fall into any well defined pattern vis-a-vis those from either juvenile wood or mature wood pulps from a given tree.

Therefore, kraft pulps from the juvenile wood section of the butt portion of each tree would be expected, because of their finer fibers, to exhibit increased interfiber bonding, leading to higher burst and tensile, but reduced tear, compared to pulps from the mature wood section of the butt portion of the same tree.

Fiber Length Distributions in Bleachable-Grade Kraft Pulps

Fiber length distributions of the 27 bleachable-grade kraft pulps from the second series of cooks were grouped by tree component as shown in Figure 11-5. Kraft pulps from juvenile wood and top wood samples had similar distribution frequencies whilst those from mature wood contained a higher proportion of long fibers. These trends are confirmed by the weight-weighted fiber length mean values of 2.75, 2.85 and 3.22 millimeters for juvenile wood, top wood and mature samples, respectively.

The pith-to-bark weighted fiber length of bleachable-grade kraft pulps determined by means of the miniature kraft cooks are shown in Figures 11-6 to 11-8 for butt samples from Ladysmith, Lizard Lake and Jordan River, respectively. The

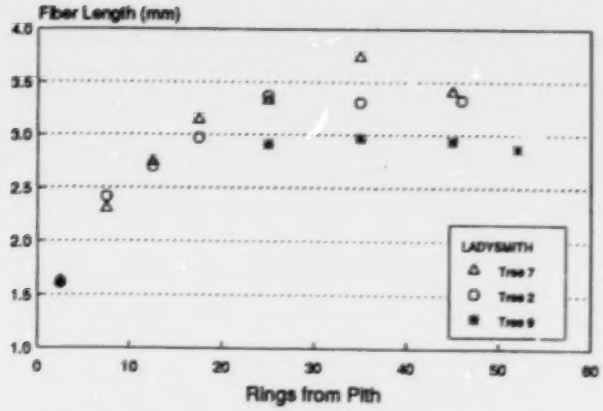


Fig. 11-6 Weight-weighted fiber length of kraft pulps versus rings from pith for butt sections of the three trees from Ladysmith

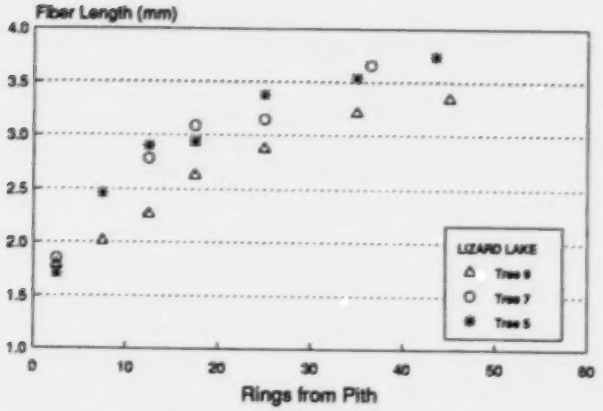


Fig. 11-7 Weight-weighted fiber length of kraft pulps versus rings from pith for butt sections of the three trees from Lizard Lake

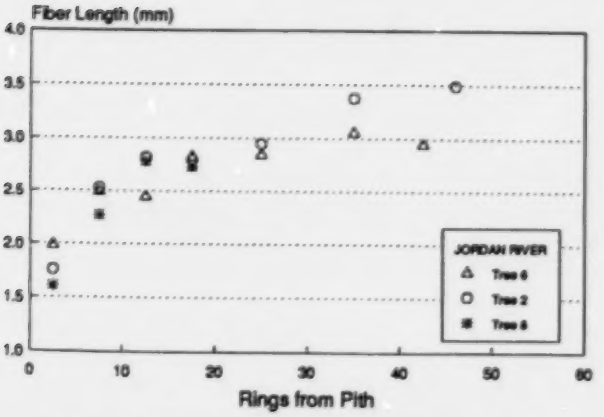


Fig. 11-8 Weight-weighted fiber length of kraft pulps versus rings from pith for butt sections of the three trees from Jordan River

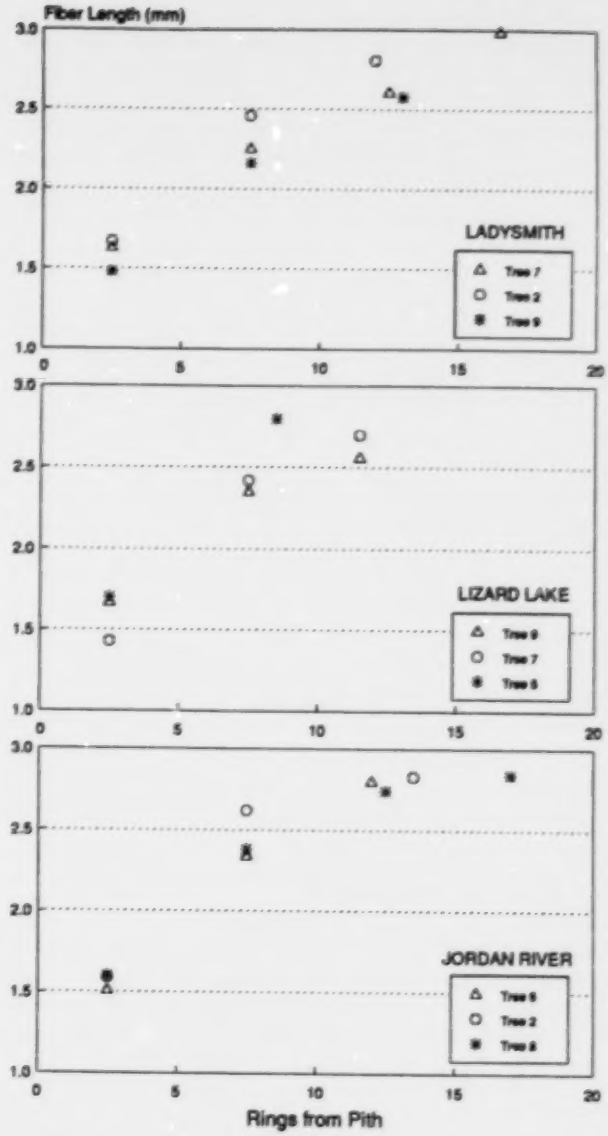


Fig. 11-9 Weight-weighted fiber length of kraft pulps versus rings from pith for top sections of the three trees from each study site

corresponding distributions for top samples are shown in Figure 11-9. It was found that fiber lengths increased rapidly for the first 20 years in both butt juvenile wood and top wood samples, after which fiber lengths continued to increase for some trees, but at a reduced rate. Tree differences were apparent, but could not be explained on a basis of chip density differences.

Weight-Weighted Fiber Length

The weight-weighted fiber lengths of the 27 bleachable-grade kraft pulps are shown in Table 11-3. They ranged from 2.39

to 3.48 millimeters, and were much more consistent than their corresponding coarseness values. For each of the nine trees, the weight-weighted fiber lengths of juvenile wood kraft pulps were consistently smaller than those of the corresponding mature wood pulps. The weight-weighted fiber lengths of top wood kraft pulps were generally intermediate in value between juvenile wood and mature wood pulps from a given tree. These trends are consistent with the pith-to-bark fiber lengths shown in Figures 11-6 to 11-9.

R-14 Bauer-McNett Fraction

The fiber fractions retained on the 14 mesh screen during Bauer-McNett fractionation of the 27 bleachable-grade kraft pulps are shown in Table 11-3. In general, R-14 values were well correlated on a within-tree basis with the weight-weighted fiber length data shown in Table 11-3, but the slopes and intercepts of the nine regression equations were different on a between-tree basis, as shown below.

Ladysmith

Tree No. 7: R-14, % = 30.4 + 12.1 WWFL; $r^2 = 0.99$
Tree No. 2: R-14, % = 31.2 + 13.1 WWFL; $r^2 = 0.69$
Tree No. 9: R-14, % = 28.6 + 13.1 WWFL; $r^2 = 0.99$

Lizard Lake

Tree No. 9: R-14, % = -49.8 + 33.5 WWFL; $r^2 = 0.99$
Tree No. 7: R-14, % = -26.5 + 27.5 WWFL; $r^2 = 0.99$
Tree No. 5: R-14, % = -20.3 + 25.4 WWFL; $r^2 = 0.95$

Jordan River

Tree No. 6: R-14, % = -17.5 + 25.1 WWFL; $r^2 = 0.81$
Tree No. 2: R-14, % = -13.4 + 23.6 WWFL; $r^2 = 0.98$
Tree No. 8: R-14, % = 22.4 + 12.2 WWFL; $r^2 = 0.99$

Handsheet Properties of Bleachable-Grade Kraft Pulps

Handsheets from unbeaten and beaten samples of the 27 bleachable-grade kraft pulps were tested for their structural, mechanical and optical properties and the complete data set is shown in Tables 11-4, 11-5 and 11-6.

In general, the development of sheet properties can be described by using a given level of beating, pulp freeness, or sheet density as a yardstick. Freeness will not be highlighted here because the trends shown are similar to those observed at a given level of beating. Important handsheet properties were analyzed to identify gross differences between tree components. These data, given in Table 11-7, quantify the following narrative which describes differences between juvenile wood, mature wood and top wood pulps.

Properties as a Function of PFI Revolutions

The rate at which selected sheet properties developed in bleachable-grade kraft pulps from juvenile wood, mature wood and top wood -- all sites combined -- is shown in Figures 11-10 to 11-18.

Structural Properties

The sheet densities of kraft pulps from juvenile wood and top wood were equivalent (Figure 11-10). These kraft pulps form denser sheets at any level of beating than those from mature wood, which agrees with the smaller coarseness values for juvenile wood and top wood pulps (Table 11-3). Handsheets from mature wood kraft pulps were rougher (Figure 11-11) than those from juvenile wood and top wood pulps -- which were similar -- and were more porous, as shown by the air resistance trends in Figure 11-12.

Mechanical Properties

At any level of beating, handsheets from juvenile wood and top wood kraft pulps showed greater interfiber bonding than those from mature wood pulps, as reflected in values of tensile index (Figure 11-13) and burst index (Figure 11-14). Kraft pulps from juvenile wood and top wood showed slightly higher stretch than those from mature wood (Figure 11-15) so that the stress-strain factors for juvenile wood and top wood pulps were equivalent and larger than those from mature wood pulps (Figure 11-16). Tear indexes of mature wood pulps were substantially larger than those from juvenile wood pulps, which were somewhat larger than those from top wood pulps (Figure 11-17) at any level of beating.

Optical Properties

Up to 3000 revolutions, scattering coefficients of pulps from mature wood were slightly lower than those from juvenile wood and top wood (Figure 11-18). Further beating, as expected, removed any differences in scattering between the three pulp types.

Pulp Freeness as a Function of PFI Revolutions

Up to 6000 revolutions, the freeness drop was slightly slower for mature wood kraft pulps than for either juvenile wood or top wood pulps, which were equivalent (Figure 11-19). To achieve comparable freeness levels, mature wood kraft pulps required about 2000 more revolutions than did juvenile wood and top wood pulps. Thus, in the freeness range from 600 to 300 milliliters (Table 11-7), kraft pulps from juvenile wood and top wood were denser, smoother and less porous to air than those from mature wood. Similarly, juvenile wood and top wood kraft pulps had higher tensile and burst indexes, but substantially lower tear indexes than mature wood kraft pulps. Kraft pulps from juvenile wood and top wood also had slightly higher stretch and higher stress-strain factors than pulps from mature wood.

Properties as a Function of Sheet Density

At sheet densities of 600 kilograms per cubic meter or less, handsheets from mature wood pulps were slightly rougher than those from juvenile wood and top wood pulps -- which were equivalent (Figure 11-20). Tensile and burst indexes of all three pulp types were similar at equivalent low sheet densities (Figures 11-21 and 11-22) but, at 600 kilograms per cubic meter, the tensile and burst of juvenile wood pulps were slightly lower than those from mature wood and top wood pulps. The stretch of mature wood pulps was slightly higher than that of juvenile wood and top wood pulps in the sheet density range from 600 to 700 kilograms per cubic meter

(Figure 11-23). At 600 kilograms per cubic meter, the stress-strain factors for juvenile wood pulps were slightly lower than those of mature wood and top wood pulps (Figure 11-24). At equivalent low sheet densities, the tear indexes of all three pulp types were similar (Figure 11-25). In the sheet density range from 600 to 700 kilograms per cubic meter, the tear indexes of juvenile wood and mature wood pulps were similar to one another and higher than those from top wood pulps.

Tear Index versus Tensile Index

Tear-tensile plots for juvenile wood, mature wood and top wood pulps, all sites combined, are shown in Figure 11-26. For tensile values below 40 or above 100 N•m/g, tear indexes of all three pulp types were similar. In the tensile index range from 60 to 80 N•m/g, the tear index of mature wood pulps was as much as 50 percent larger than those from juvenile wood pulps which, in turn, were about 10 percent higher than those from top wood pulps.

Tensile Index versus Scattering Coefficient

Tensile index/scattering coefficient plots for juvenile wood, mature wood and top wood pulps, all sites combined, are shown in Figure 11-27. At any given value of scattering, tensile index was similar for juvenile wood and top wood pulps which were higher than those from mature wood pulps.

Effects of Wood Density and Fiber Properties on Sheet Properties

In planning the new forest, or in preparation for utilization of second-growth stands, it is important that the effects of wood density and fiber properties on pulp properties be identified and quantified. We need to know whether an increase in wood density merely gives more woody material per cubic meter, or if there are useful relationships between density, fiber properties and handsheet properties. These could be used to assess the effects of stand management practices on the properties and quality of end products made from this resource, and to predict the pulp properties of improved planting stock.

Various authors have attempted to related wood and fiber morphological properties to handsheet properties, particularly for softwood kraft pulps. Early work by Kellogg *et al.* (1975a, 1975b, 1976) on western hemlock and by Matolcsy (1975) on balsam fir are notable Canadian efforts in this area. The equations derived were quite successful in predicting the effects of wood quality changes on pulp strength (Kellogg and Gonzalez, 1976). Matolcsy (1975) found that fiber dimension ratios were not useful in predicting the physical properties of pulp.

In much of this early pioneering work, fiber dimensions such as length, diameter, cell wall thickness, and fibril angle could only be determined by tedious, time-consuming, and often expensive methods in which accuracy was often at a premium. The recent development, however, of more rapid techniques to measure fiber length (Bichard and Scudamore, 1988), fiber coarseness (Bichard and Scudamore, 1988), and fibril angle (Senft and Bendtsen, 1985), now offers new approaches to, and increased incentive for, studies of relationships between wood properties, fiber properties and handsheet properties.

In the context of second-growth forests and trees harvested in the 21st century, the ultimate goal must be to develop relationships between a few significant wood and fiber properties and handsheet properties and, from these, to develop appropriate models which can be used to define well in advance of harvest those options available for best use of a managed stand of trees for specific fiber products. A second and related goal must be to develop accurate methodology for the prediction of fiber properties in trees approaching their rotation age based on the fiber characteristics of juvenile trees less than 5, or at most 10, years old.

There is increasing evidence to show that for some species, particularly *Pinus*, kraft pulp handsheet properties are well correlated with wood (chip) density alone, or in combination with certain easily-measured significant fiber properties. This is nicely illustrated by Semke's (1984) review of the effects of juvenile fibers from loblolly and slash pine on kraft paper properties. Increasing juvenile wood density led to reduced bursting strength, breaking length and handsheet density of the resulting kraft papers. Tearing resistance increased. These trends are qualitatively in agreement with those discussed in this Chapter for second-growth Douglas-fir kraft pulps.

Detailed studies of Kibblewhite and coworkers (1980, 1982, 1983a, 1983b, 1984a, 1984b) in the past decade on *P. radiata* from New Zealand confirm these earlier studies and support even more strongly the high degree of correlation between chip density and various properties of kraft pulp handsheets made from trees ranging in age from 12 to 52 years.

A similar approach was taken with the 27 bleachable-grade kraft pulps from second-growth Douglas-fir whose properties were adjusted to 1000 revolutions in a PFI mill as described earlier. Values of sheet density, tensile index, stretch, burst index, and tear index for the 27 bleachable-grade kraft pulps beaten to 1000 revolutions in a PFI mill are shown in Table 11-8.

The summary statistics from the data used to develop the prediction equations are shown in Table 11-9. The broad ranges observed for each variable suggest that prediction equations involving these variables should be widely applicable to the future Douglas-fir resource.

The correlation coefficients (r) for each pair of variables are shown in Table 11-10. Among dependent variables, tensile index and burst index were highly correlated ($r = 0.99$) as expected. Stretch was strongly correlated with sheet density ($r = 0.86$) while other pairs were moderately (yet significantly) linearly related. Among independent variables, disk density and chip density were highly correlated ($r = 0.99$) as shown in Chapter 10. Thus, in the development of prediction equations, separate equations were developed for chip and disk densities.

The former will be appropriate for future quality control purposes during the pulping process while the latter will be more appropriate when it is required to predict the properties of handsheets manufactured from kraft pulps from trees for which disk densities are available.

Those independent variables which play a significant role in one, two or three independent variable prediction models for the dependent variables sheet density, tensile index, stretch, burst index, and tear index are summarized in Table 11-11 for the independent variables of disk density and chip density. Values of R^2 show that for the properties of sheet density, tensile index and burst index, the single most important variable was disk or chip density. The addition of fiber coarseness and weight-weighted fiber length produced significant increases in R^2 values. Although disk and chip density were important single variables for the property of tear index, the best fit was obtained with fiber length. The two variable equations with fiber length and disk density or chip density gave significantly larger R^2 values of 0.85 and 0.84 respectively. Fiber coarseness was the single most important variable for the property of stretch, with $R^2 = 0.55$. The two variable models containing disk density or chip density were considered better than the three variable models containing fiber length.

The three variable prediction equations chosen as models from this analysis are shown in Tables 11-12 and 11-13, respectively, when disk density and chip density were used as the independent variable for density. Figures 11-28 to 11-32 show the predicted versus observed values of the five dependent variables based on chip density as the independent variable. We conclude that the wide ranging properties of kraft pulp handsheets made from three different components within nine second-growth Douglas-fir trees ranging widely in wood density, can be predicted and explained on a basis of wood or chip density, fiber length and fiber coarseness. This finding is important not only because these three parameters can be relatively easily measured but, because with more research into the ways trees grow, we anticipate having some degree of control over these and other parameters in the future.

Options for Utilization of Shorter Rotation Douglas-Fir

Future forest crops under some degree of management will be harvested in rotations shorter than those presently used. This change will likely bring about an increase in the ratio of juvenile to mature wood in a tree depending upon the relative growth rates of each wood type and the age of the tree at harvest. In the present study, and based on a total of 60 trees (10 trees from each of six sites), the amount of juvenile wood in a stem, i.e., from the butt to the unmerchantable top, was determined to be 49 percent for Douglas-fir trees with a mean age of 50 years (Chapter 1).

Four potential utilization options are considered to illustrate the effects of juvenile wood in the kraft pulping of second-growth Douglas-fir.

1. 50-year old trees are processed for solid products, and sawmill residual chips consisting of mature wood are processed into pulp. This is equivalent to present practice.
2. 50-year old trees are sawn to segregate juvenile wood for use in pulping. Mature wood is converted to solid products with approximately 20 percent residual chips processed into pulp.
3. 50-year old trees grown as pulpwood are sawn to segregate juvenile and mature wood. Mature wood and juvenile wood chips could be processed for pulp either separately or together in prescribed ratios to produce pulps with specific qualities.
4. Managed Douglas-fir stands could be thinned at 20 years, for example. To a first approximation, the results for top wood samples in the present study (Chapters 10 and 11) can be used to indicate the quality of kraft pulps from thinnings.

Values of sheet density, tensile index and tear index of 27 Douglas-fir kraft pulps beaten for 1000 revolutions in a PFI mill are shown in Table 11-14 for juvenile wood, mature wood and top wood and the four utilization options.

The most significant features of Table 11-14 are as follows. The use of increasing quantities of juvenile wood (including thinnings) has a significantly adverse affect on tear index, although it should be noted that tear index values of 20, though on the low side for Douglas-fir, are comparable to whole-stem pulps from other Canadian softwoods. This drop in tear is offset to some extent by increased tensile index and sheet density. The ranges in values of sheet density, tensile index and tear index shown suggest that this species offers a number of utilization options whereby a range of kraft pulps with distinctive properties can be prepared. Other softwoods may not be capable of ranges with comparable magnitudes.

The development of a model simulation the conversion of this resource to pulp, PULPSIM, would parallel the conversion to dimension lumber using SAWSIM as described in Chapter 13. A model such as this will permit an evaluation of the financial impact of these and other utilization options.

Table 11-4. Handsheet Physical Properties of Bleachable-Grade Kraft Pulps from Second-Growth Douglas-Fir (Site: Ladysmith)

Tree No.	Wood Sample	PFI revs, x10^3	Csf ml	Sheet Density kg/m^3	Sheffield Roughness	Air Resistance s/100 ml	Tensile Index N•m/g	Stretch %	Stress-Strain Factor mJ/g	Burst Index kPa•m^2/g	Tear Index mN•m^2/g	Scattering Coefficient cm^2/g
7	JW	0	742	336	377	0	22	1.24	200	1.2	13.5	318
		3	702	588	294	0	82	2.71	1506	5.7	24.1	185
		6	575	614	251	5	90	3.08	1826	7.2	21.8	168
		12	271	649	99	120	106	3.29	2300	8.1	19.1	165
	MW	0	764	319	401	0	15	0.98	108	0.8	12.0	272
		3	716	535	352	0	68	2.52	1178	4.6	35.3	176
		6	646	556	323	0	76	2.75	1451	5.3	34.4	170
		12	283	588	168	37	88	3.25	1957	6.6	28.2	176
	TW	0	731	405	348	0	29	1.56	321	1.6	17.5	366
		3	689	621	270	4	88	3.08	1805	6.6	18.0	197
		6	585	645	232	11	101	3.46	2275	8.0	16.0	173
		12	327	667	109	96	107	3.48	2443	8.7	14.8	166
2	JW	0	738	388	346	0	28	1.80	361	1.8	16.0	344
		3	688	614	263	4	89	3.17	1868	6.7	23.1	199
		6	584	637	237	8	99	3.68	2379	8.0	19.0	179
		12	314	671	99	126	112	3.44	2531	8.8	17.7	171
	MW	0	763	376	376	0	23	1.45	241	1.3	16.9	308
		3	698	565	324	0	87	2.65	1585	5.8	29.6	195
		6	602	592	269	4	83	3.36	1888	6.6	25.8	178
		12	271	629	133	68	93	3.62	2267	7.5	23.0	172
	TW	0	731	424	344	0	29	1.49	309	1.6	18.1	328
		3	691	595	283	3	84	2.94	1657	6.7	19.8	193
		6	603	633	242	7	98	3.44	2228	7.9	17.3	173
		12	326	645	112	81	106	3.45	2438	8.5	16.9	169
9	JW	0	698	505	255	3	48	1.94	628	3.0	24.1	315
		3	623	641	193	13	106	2.98	2098	7.5	17.5	206
		6	557	680	142	36	108	3.55	2465	8.4	16.2	176
		12	309	704	71	253	114	3.78	2795	9.3	15.1	169
	MW	0	746	417	349	0	24	1.53	261	1.4	15.5	320
		3	696	610	280	3	78	2.77	1438	5.7	24.0	195
		6	604	629	250	8	90	3.28	1948	7.1	20.5	180
		12	337	658	112	90	105	3.30	2274	8.1	17.4	172
	TW	0	728	418	345	0	31	1.70	364	1.8	16.8	328
		3	662	625	254	5	90	3.02	1786	6.8	17.5	193
		6	589	649	223	14	99	3.36	2159	7.6	16.1	171
		12	352	676	108	124	108	3.43	2388	8.6	14.5	156

Table 11-5. Handsheet Physical Properties of Bleachable-Grade Kraft Pulps from Second-Growth Douglas-Fir (Site: Lizard Lake)

Tree No.	Wood Sample	PFI revs. x10^3	Csf ml	Sheet Density kg/m^3	Sheffield Roughness	Air Resistance s/100 ml	Tensile Index N·m/g	Stretch %	Stress-Strain Factor mJ/g	Burst Index kPa·m^2/g	Tear Index mN·m^2/g	Scattering Coefficient cm^2/g
9	JW	0	721	382	366	0	24	1.28	214	1.2	11.0	354
		3	683	592	303	0	64	2.91	1325	4.2	18.7	213
		6	587	625	280	4	73	3.37	1714	5.5	18.6	193
		12	286	667	115	94	88	3.66	2225	6.7	16.6	168
	MW	0	753	332	397	0	18	1.20	157	0.9	9.8	318
		3	718	538	349	0	55	2.67	986	3.7	26.1	204
		6	599	575	320	0	69	3.01	1455	4.9	25.4	174
		12	277	614	153	53	79	3.19	1764	6.0	22.3	166
	TW	0	730	375	367	0	24	1.24	207	1.1	10.1	365
		3	694	588	301	0	67	2.72	1268	4.7	17.7	206
		6	598	621	260	6	85	3.28	1899	6.2	16.2	181
		12	315	658	111	96	94	3.43	2186	7.3	14.4	166
7	JW	0	731	389	363	0	22	1.17	176	1.1	11.4	347
		3	693	614	283	3	75	2.55	1278	5.0	20.3	209
		6	606	629	258	5	86	2.99	1707	6.5	18.0	190
		12	406	667	145	52	95	3.85	2442	7.4	16.0	163
	MW	0	756	340	396	0	20	1.08	147	1.0	12.4	319
		3	715	575	341	0	68	2.56	1180	4.8	27.3	181
		6	626	588	320	2	81	2.81	1549	6.5	22.3	169
		12	315	621	160	49	91	3.38	2067	7.2	19.3	160
	TW	0	728	405	344	0	29	1.28	253	1.5	15.4	348
		3	666	610	262	4	91	2.89	1728	6.4	15.9	200
		6	564	654	205	14	111	3.34	2391	8.5	13.6	174
		12	320	680	95	124	115	3.54	2624	9.3	12.1	155
5	JW	0	722	407	337	0	24	1.48	259	1.3	15.8	330
		3	689	629	245	5	76	2.99	1554	5.6	17.8	197
		6	630	654	231	9	91	3.49	2127	6.9	14.9	173
		12	384	694	97	123	106	3.61	2490	8.2	12.9	161
	MW	0	748	373	387	0	19	1.27	172	1.0	14.2	312
		3	734	552	335	0	62	2.45	1047	4.4	25.6	204
		6	674	606	315	2	78	3.01	1599	5.9	19.3	180
		12	391	629	194	31	88	3.16	1868	7.0	16.3	166
	TW	0	730	402	345	0	26	1.58	290	1.5	14.6	352
		3	683	599	263	6	86	2.54	1506	6.0	13.9	215
		6	618	641	214	14	102	3.08	2074	7.7	11.8	179
		12	360	671	126	155	113	3.26	2403	8.9	10.6	164

Table 11-6. Handsheet Physical Properties of Bleachable-Grade Kraft Pulps from Second-Growth Douglas-Fir (Site: Jordan River)

Tree No.	Wood Sample	PFI revs, x10^3	Csf ml	Sheet Density kg/m^3	Sheffield Roughness	Air Resistance s/100 ml	Tensile Index N·m/g	Stretch %	Stress-Strain Factor mJ/g	Burst Index kPa·m^2/g	Tear Index mN·m^2/g	Scattering Coefficient cm^2/g
6	JW	0	745	415	341	0	28	1.66	304	1.6	13.8	336
		3	677	610	267	3	70	2.91	1403	5.1	22.1	213
		6	587	641	247	5	82	3.33	1866	6.0	19.5	185
		12	363	685	144	36	89	3.71	2250	6.9	17.8	164
	MW	0	754	402	385	0	24	1.11	181	1.1	13.3	306
		3	711	585	336	0	62	2.66	1136	4.3	27.5	190
		6	618	599	312	0	75	3.21	1641	5.6	23.5	174
		12	321	629	197	17	84	3.52	2014	6.5	21.3	166
	TW	0	740	412	361	0	33	1.53	360	1.8	18.2	316
		3	680	571	309	0	80	2.74	1489	6.1	19.4	194
		6	602	595	292	4	96	2.98	1915	7.4	17.5	168
		12	347	629	172	29	105	3.26	2264	8.2	15.8	155
2	JW	0	739	488	326	0	35	1.80	443	2.0	21.7	291
		3	679	610	275	3	72	3.02	1521	5.3	20.9	192
		6	588	637	254	6	85	3.18	1864	6.5	18.1	173
		12	378	667	143	38	92	3.52	2232	7.2	17.5	151
	MW	0	752	394	378	0	29	1.29	258	1.3	16.0	307
		3	712	559	335	0	64	2.66	1153	4.5	30.2	201
		6	643	585	320	0	77	3.15	1627	5.6	28.0	177
		12	350	621	195	22	83	3.48	1941	6.7	24.6	157
	TW	0	728	448	330	0	37	1.57	389	2.1	17.6	320
		3	676	592	288	3	82	3.03	1650	6.1	18.5	202
		6	581	625	257	6	97	3.13	1977	7.5	16.6	173
		12	359	654	151	37	103	3.54	2380	8.5	15.0	150
8	JW	0	727	465	293	0	39	1.94	532	2.5	19.7	300
		3	686	629	241	5	82	3.06	1699	6.2	19.4	195
		6	586	667	206	12	94	3.35	2103	7.0	17.8	168
		12	328	694	93	110	104	3.54	2470	8.0	15.3	151
	MW	0	749	403	362	0	28	1.35	249	1.4	16.4	296
		3	709	588	311	0	70	2.72	1274	5.1	29.3	185
		6	615	610	287	4	88	3.23	1880	6.6	24.5	165
		12	309	654	136	47	97	3.37	2152	7.4	20.3	149
	TW	0	726	461	313	0	39	1.62	429	2.3	20.3	324
		3	679	629	253	5	90	3.19	1892	6.8	17.9	188
		6	598	649	232	9	101	3.31	2200	8.2	16.0	166
		12	335	676	113	75	114	3.66	2716	9.0	14.5	147

Table 11-7. Selected Handsheet Physical Properties[1] of Bleachable-Grade Kraft Pulps from Second-Growth Douglas-Fir Tree Components --All Sites Combined

Property	Wood Sample	PFI Revolutions 0	3000	6000	12000
Csf, ml	JW	729(14)[2]	680(21)	589(19)	338(44)
	MW	754(6)	712(11)	625(23)	317(36)
	TW	730(4)	680(10)	593(15)	338(16)
Sheet density, kg/m^3	JW	415(56)	614(16)	643(20)	678(17)
	MW	373(33)	567(23)	593(20)	627(20)
	TW	417(24)	603(18)	635(18)	662(16)
Sheffield roughness	JW	334(36)	263(31)	234(38)	112(25)
	MW	381(16)	329(21)	302(25)	161(29)
	TW	344(15)	276(19)	240(25)	122(23)
Tensile index, N·m/g	JW	30(9)	80(12)	90(10)	101(9)
	MW	22(4)	68(9)	80(6)	90(7)
	TW	31(5)	84(7)	98(7)	107(6)
Stress-strain factor, mJ/g	JW	302(172)	1584(250)	2006(263)	2145(176)
	MW	197(53)	1220(177)	1671(178)	2034(164)
	TW	325(65)	1642(182)	2124(160)	2427(153)
Tear index, $mN·m^2/g$	JW	16(4)	20(2)	18(2)	16(2)
	MW	14(2)	28(3)	25(4)	21(3)
	TW	17(3)	18(2)	16(2)	14(2)

1. Each number is the mean of nine samples
2. Figures in parentheses are standard deviations; they are included only to show the spread of data observed and are not intended for use in testing for statistical significance.

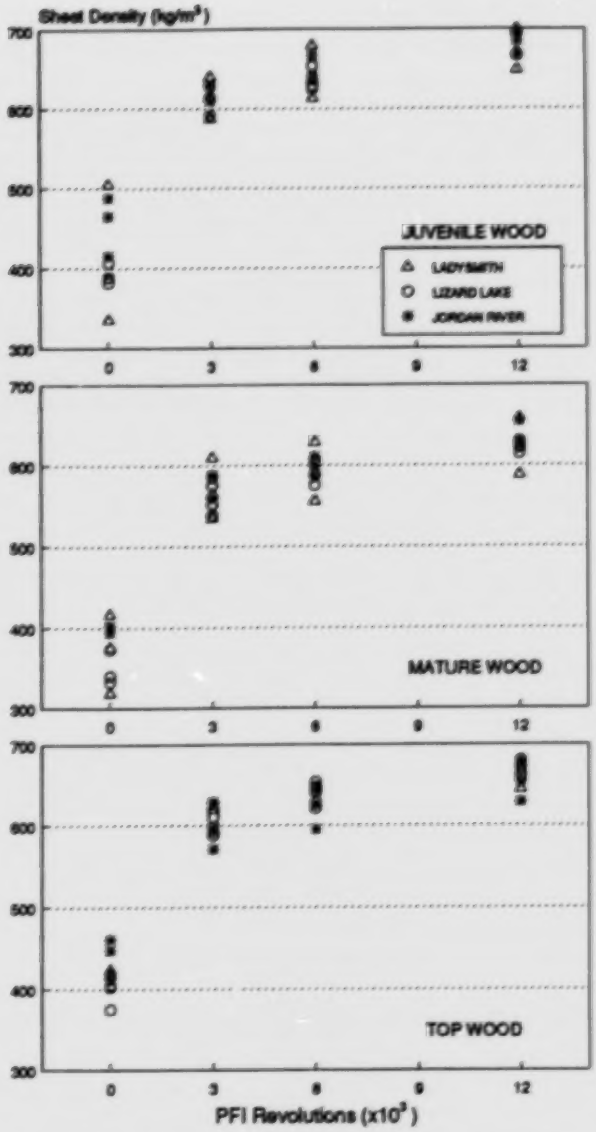


Fig. 11-10 Development of sheet density with PFI mill beating for bleachable-grade kraft pulps from juvenile, mature and top wood

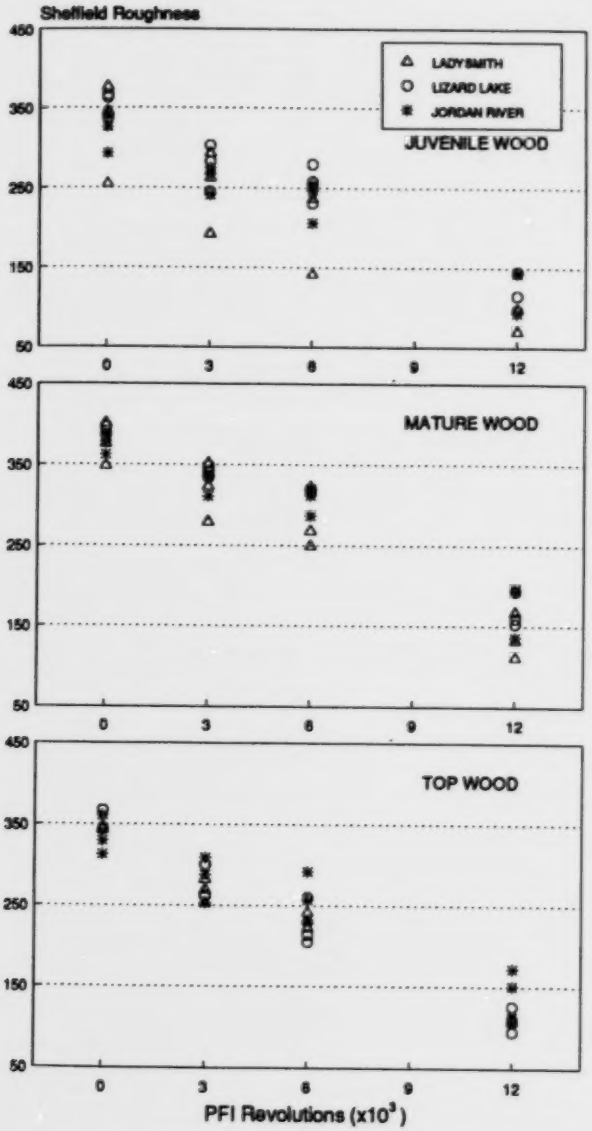


Fig. 11-11 Reduction of Sheffield roughness with PFI mill beating for bleachable-grade kraft pulps from juvenile, mature and top wood

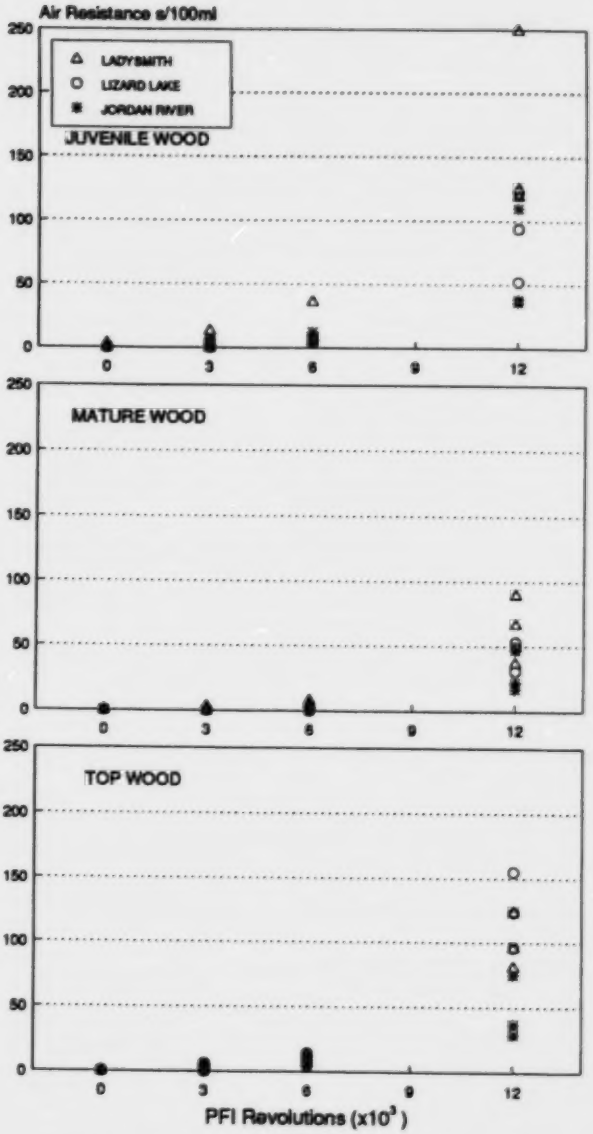


Fig. 11-12 Development of porosity with PFI mill beating for bleachable-grade kraft pulps from juvenile, mature and top wood

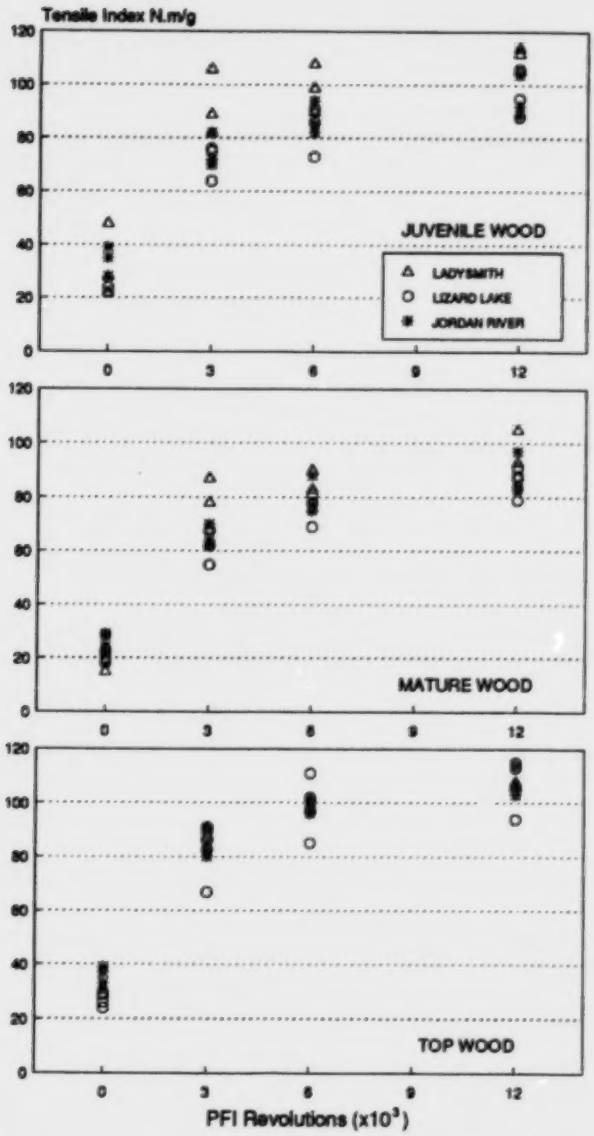


Fig. 11-13 Development of tensile index with PFI mill beating for bleachable-grade kraft pulps from juvenile, mature and top wood

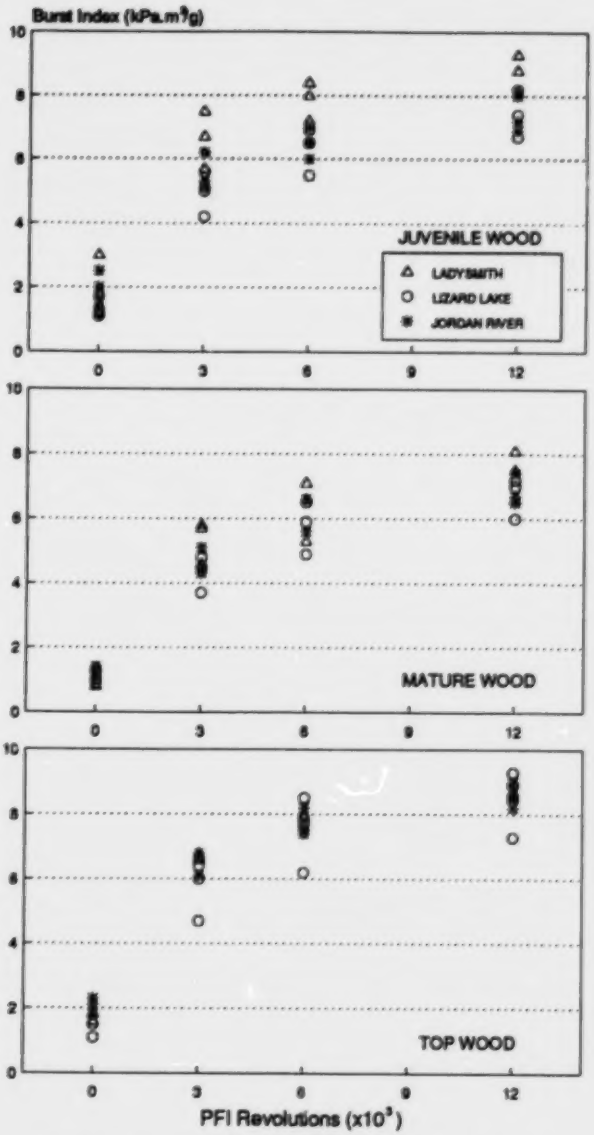


Fig. 11-14 Development of burst index with PFI mill beating for bleachable-grade kraft pulps from juvenile, mature and top wood

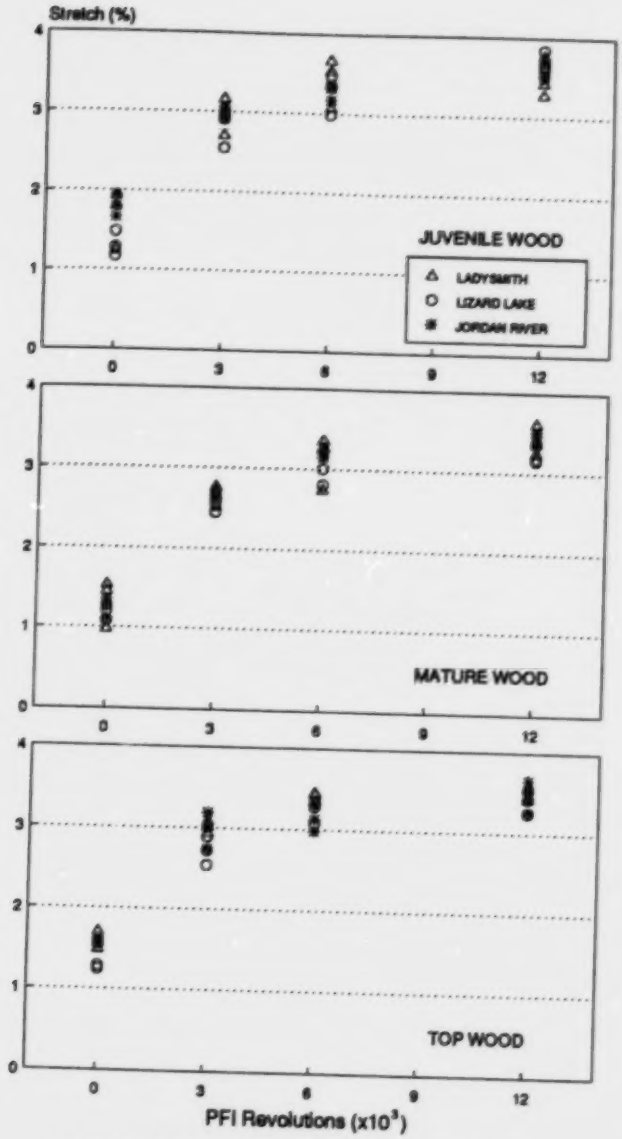


Fig. 11-15 Development of stretch with PFI mill beating for bleachable-grade kraft pulps from juvenile, mature and top wood

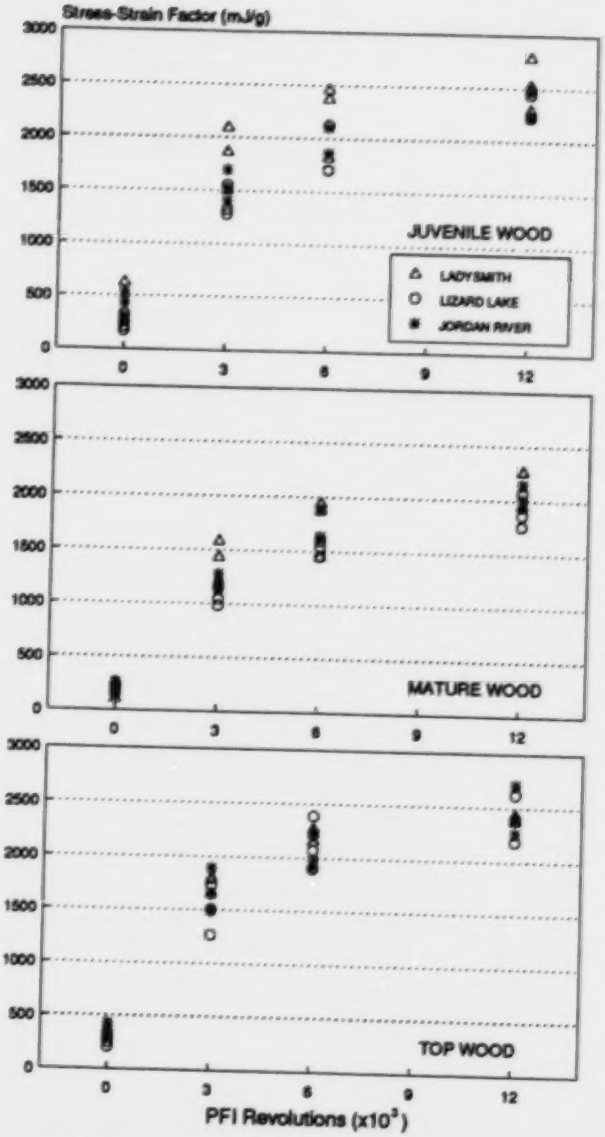


Fig. 11-16 Development of stress-strain factor with PFI mill beating for bleachable-grade kraft pulps from juvenile, mature and top wood

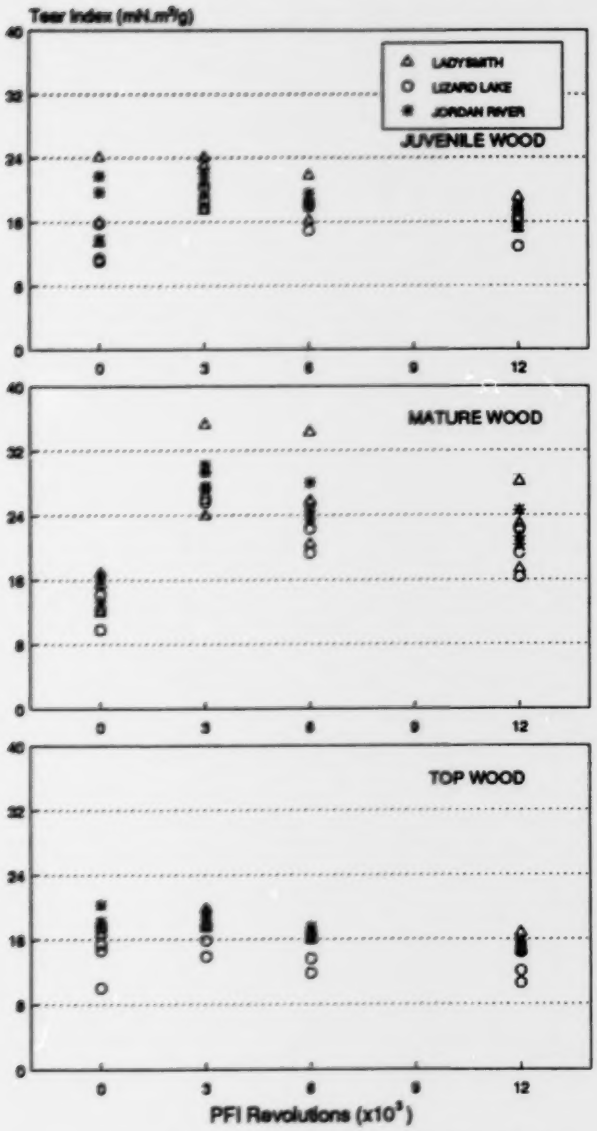


Fig. 11-17 Development of tear index with PFI mill beating for bleachable-grade kraft pulps from juvenile, mature and top wood

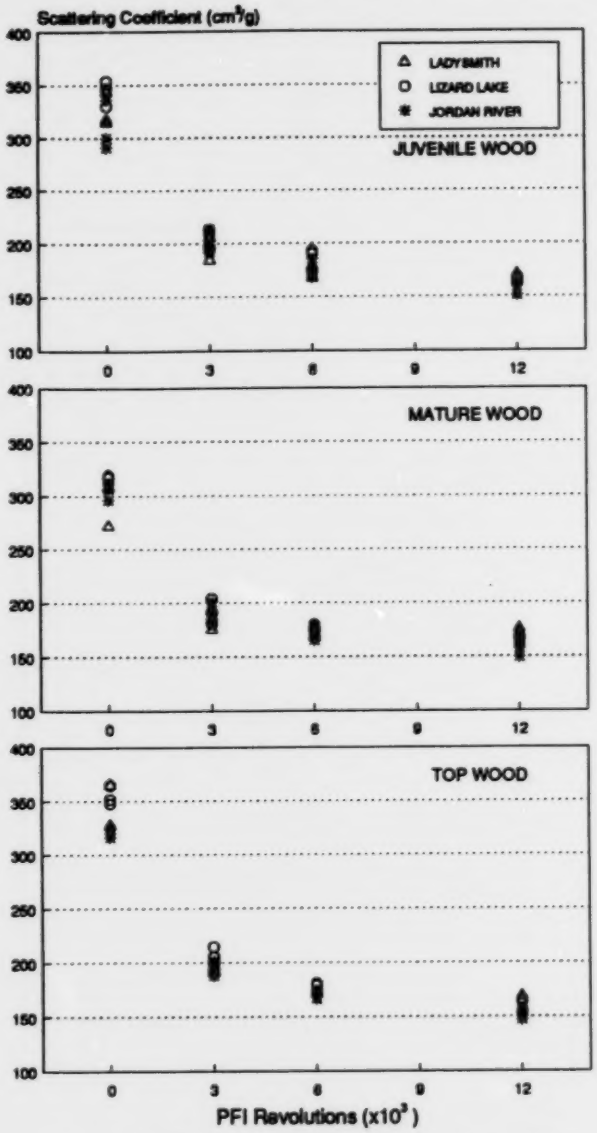


Fig. 11-18 Reduction of initial scattering coefficient with PFI mill beating for bleachable-grade kraft pulps from juvenile, mature and top wood

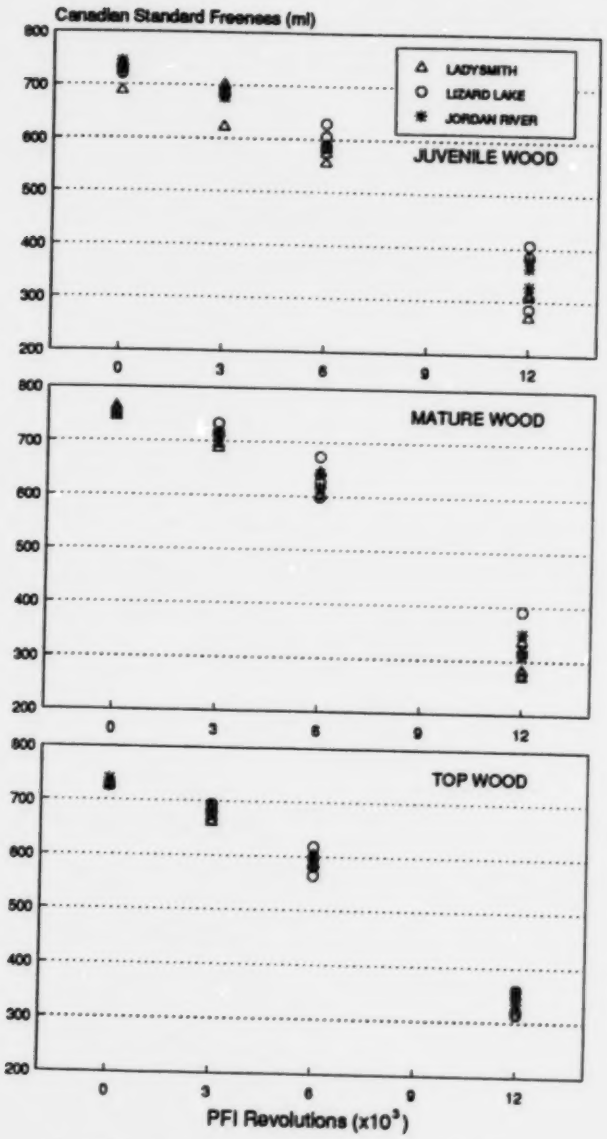


Fig. 11-19 Reduction in freeness with PFI mill beating for bleachable-grade kraft pulps from juvenile, mature and top wood

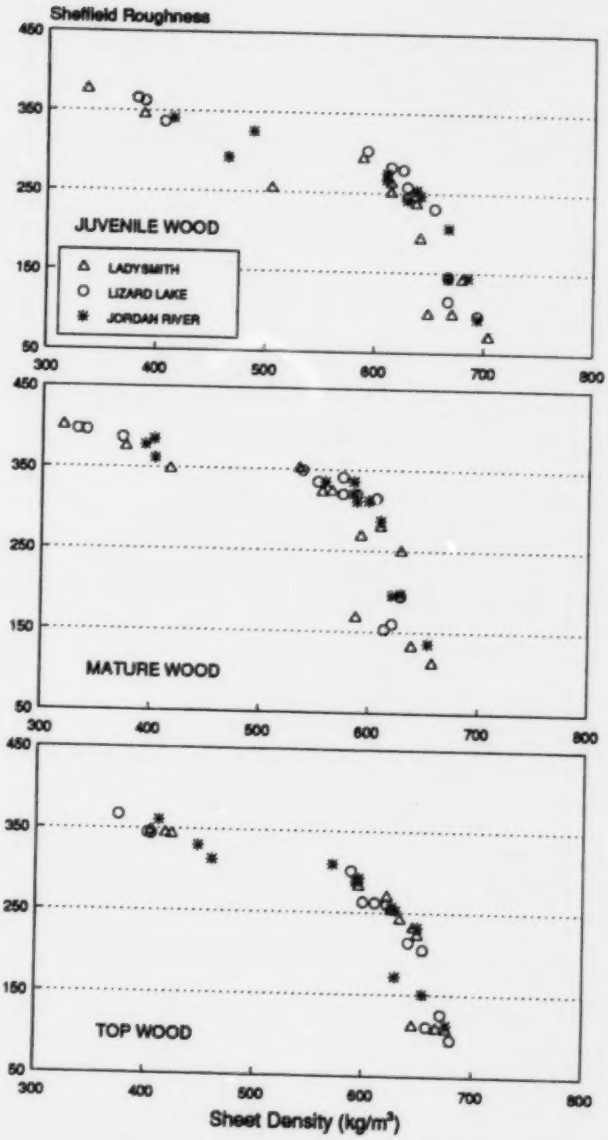


Fig. 11-20 Sheffield roughness versus sheet density for kraft pulps from juvenile, mature and top wood

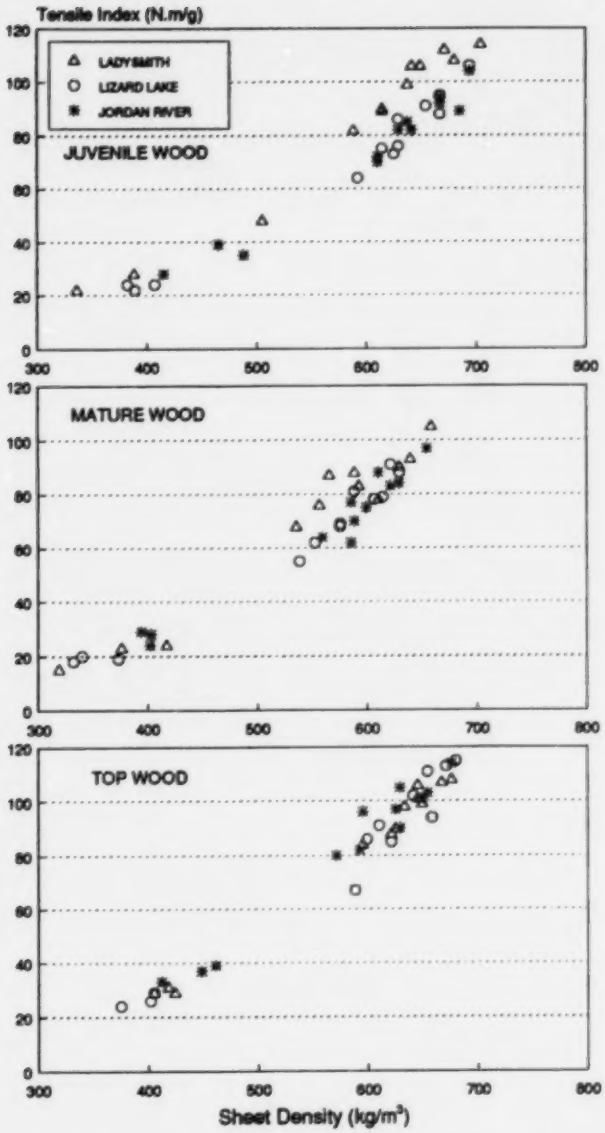


Fig. 11-21 Tensile index versus sheet density for kraft pulps from juvenile mature and top wood

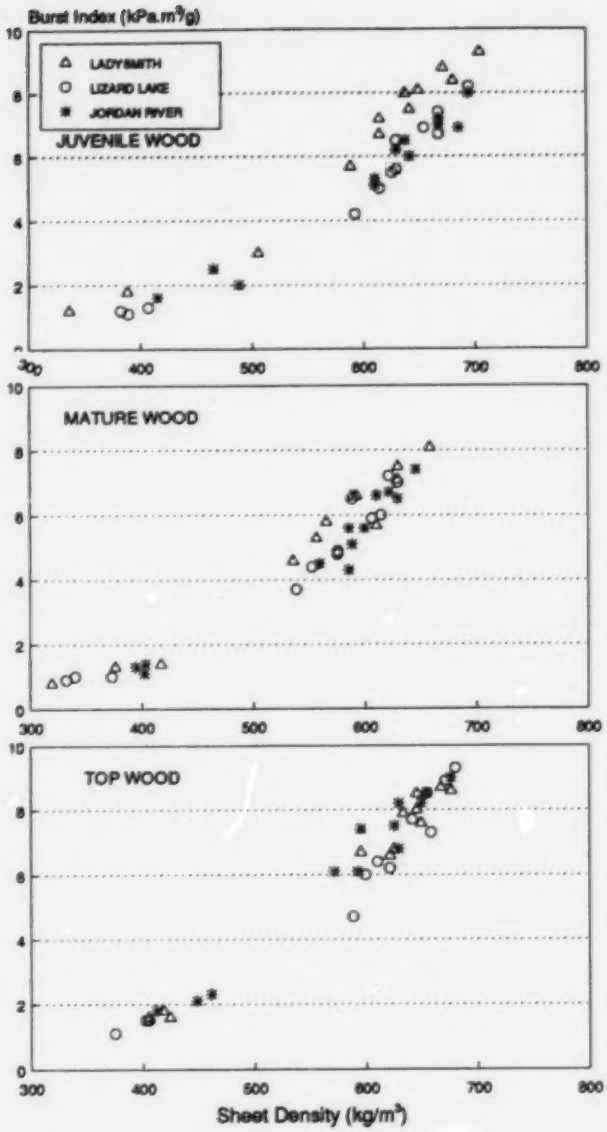


Fig. 11-22 Burst index versus sheet density for kraft pulps from juvenile mature and top wood

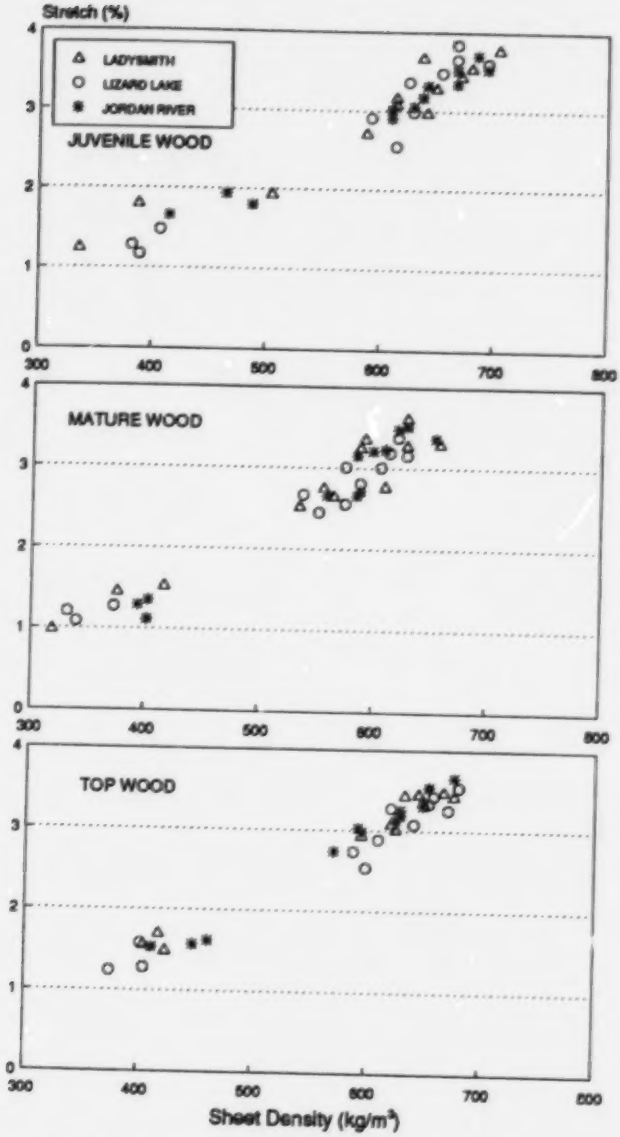


Fig. 11-23 Stretch versus sheet density for kraft pulps from juvenile, mature and top wood

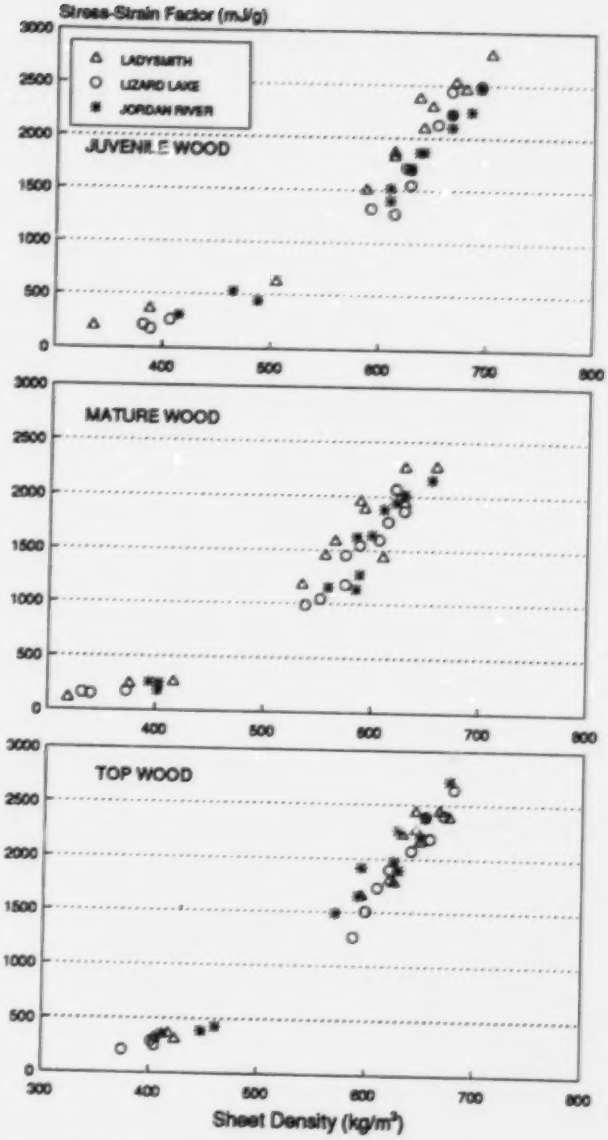


Fig. 11-24 Stress-strain factor versus sheet density for kraft pulps from juvenile, mature and top wood

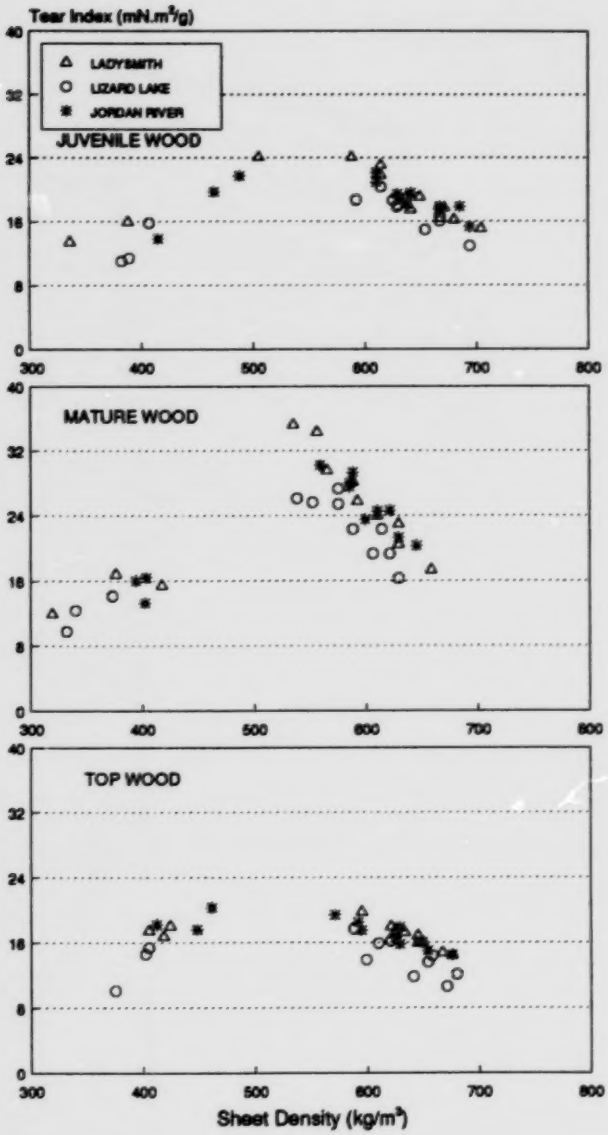


Fig. 11-25 Tear index versus sheet density for kraft pulps from juvenile, mature and top wood

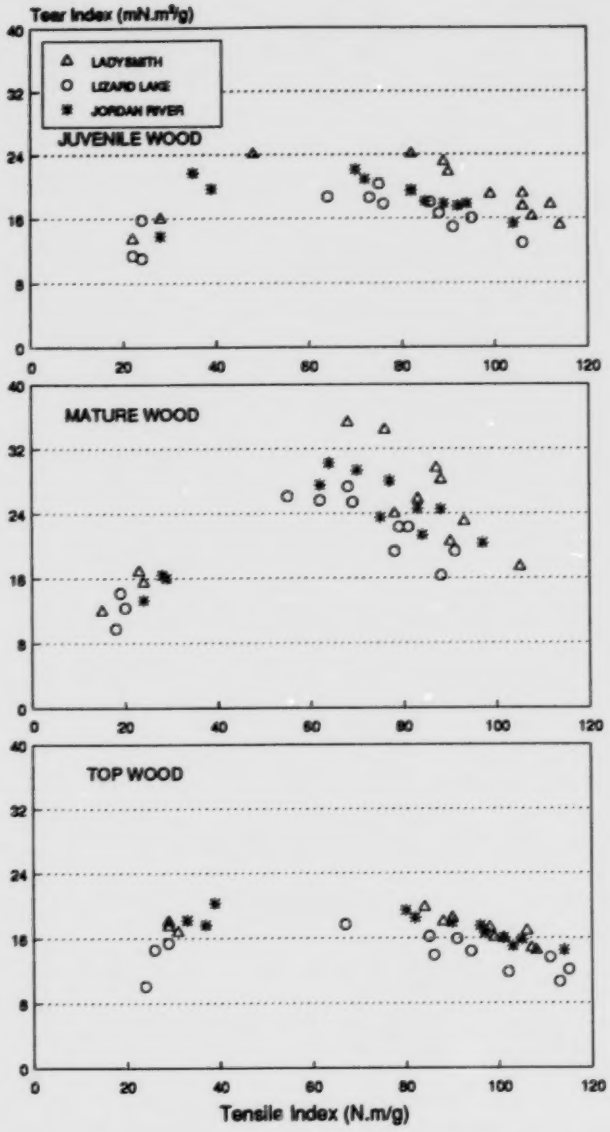


Fig. 11-26 Tear index versus tensile index for kraft pulps from juvenile, mature and top wood

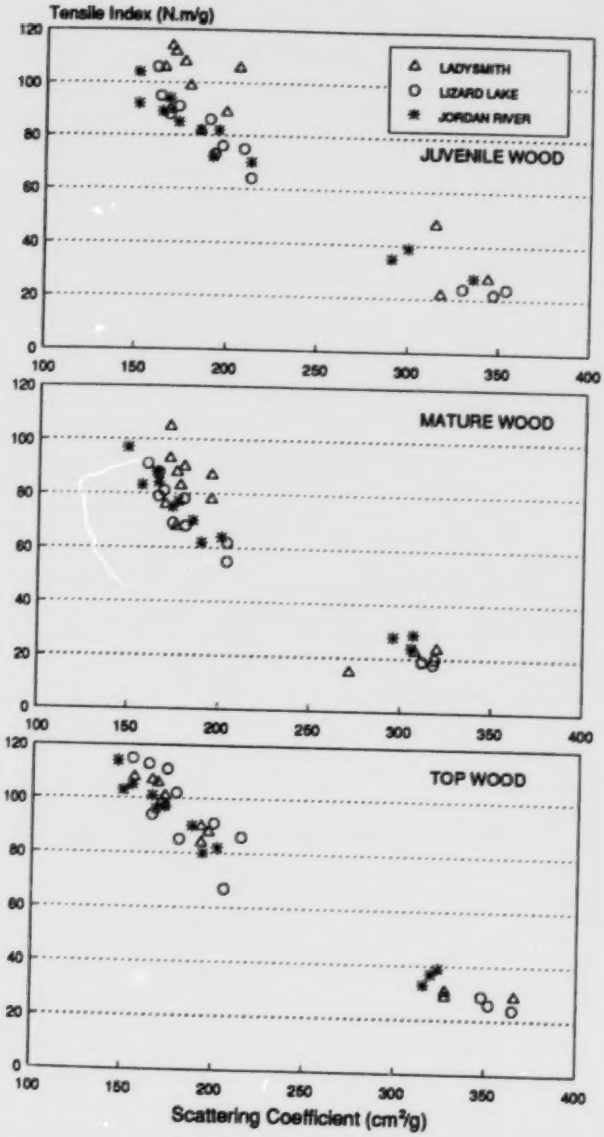


Fig. 11-27 Tensile index versus scattering coefficient for kraft pulps from juvenile, mature and top wood

Table 11-8. Handsheet Physical Properties after 1000 Revolutions in a PFI Mill of Bleachable-Grade Kraft Pulps from Second-Growth Douglas-Fir

Tree No.	Wood Sample	Sheet Density kg/m³	Tensile Index N·m/g	Stretch %	Burst Index kPa·m²/g	Tear Index mN·m²/g
			Ladysmith			
7	JW	559	78	2.66	5.8	26.4
	MW	510	65	2.46	4.5	39.5
	TW	595	84	2.97	6.5	19.7
2	JW	589	84	3.10	6.6	24.6
	MW	550	74	2.85	5.3	30.7
	TW	583	82	2.91	6.5	20.5
9	JW	640	97	3.13	7.3	17.6
	MW	588	77	2.79	5.8	26.6
	TW	602	85	2.95	6.5	18.9
			Lizard Lake			
9	JW	578	65	2.90	4.6	19.4
	MW	526	58	2.60	4.1	27.1
	TW	592	68	2.68	4.9	18.9
7	JW	586	72	2.73	5.2	21.9
	MW	542	68	2.54	5.1	31.3
	TW	598	90	2.85	6.7	16.6
5	JW	607	77	2.98	5.8	19.0
	MW	550	64	2.55	4.8	25.9
	TW	589	85	2.68	6.3	14.3
			Jordan River			
6	JW	598	70	2.98	5.1	22.5
	MW	563	64	2.72	4.6	29.5
	TW	560	81	2.69	6.1	19.9
2	JW	607	73	2.94	5.4	20.7
	MW	549	65	2.73	4.7	31.2
	TW	588	82	2.89	6.3	18.7
8	JW	622	82	3.03	6.1	20.1
	MW	573	73	2.74	5.3	30.5
	TW	612	89	3.02	6.8	18.9

Table 11-9. Summary Statistics from the Data Used to Develop the Prediction Equations for Douglas-Fir Kraft Pulps

Variable	Sample Size	Mean	Standard Deviation	Min.	Max.
Sheet density (SHEET)	27	587.7	29.8	510	640
Tensile index (TENS)	27	76.0	9.6	58	97
Stretch (STRCH)	27	2.82	0.18	2.46	3.13
Burst index (BURST)	27	5.7	0.8	4.1	7.3
Tear index (TEAR)	27	23.4	5.9	14.3	39.5
Disk density (DDEN)	27	425.6	56.5	319	558
Chip density (CDEN)	27	419.7	50.7	325	534
Weight-weighted Fiber length (FL)	27	2.94	0.27	2.39	3.48
Fiber coarseness (FC)	27	217.6	24.6	170	269
R-14 fraction (R14)	27	58.5	10.4	31.0	73.5

Table 11-10. Correlation Coefficients (r)

	Dependent Variables					Independent Variables				
	SHEET	TENS	STRCH	BURST	TEAR	DDEN	CDEN	FL	FC	R14
SHEET	1.00	0.75	0.86	0.74	-0.75	-0.70	-0.71	-0.65	-0.68	-0.21
TENS	0.75	1.00	0.66	0.99	-0.63	-0.79	-0.82	-0.33	-0.37	0.18
STRCH	0.86	0.66	1.00	0.67	-0.58	-0.49	-0.49	-0.63	-0.74	-0.08
BURST	0.74	0.99	0.67	1.00	-0.63	-0.80	-0.82	-0.31	-0.39	0.22
TEAR	-0.75	-0.63	-0.58	-0.63	1.00	0.72	0.71	0.75	0.31	0.54
DDEN	-0.70	-0.79	-0.49	-0.80	0.72	1.00	0.99	0.25	0.17	-0.02
CDEN	-0.71	-0.82	-0.49	-0.82	0.71	0.99	1.00	0.26	0.20	-0.05
FL	-0.65	-0.33	-0.63	-0.31	0.75	0.25	0.26	1.00	0.57	0.70
FC	-0.68	-0.37	-0.74	-0.39	0.31	0.17	0.20	0.57	1.00	0.03
R14	-0.21	0.18	-0.08	0.22	0.54	-0.02	-0.05	0.70	0.03	1.00

Table 11-11. Prediction Equations of Kraft Pulp Handsheet Properties from Density and Fiber Properties

Dependent Variable		Disk Density	R^2	Chip Density	R^2
Sheet Density	(1)	DDEN	0.50	CDEN	0.50
	(2)	DDEN, FC	0.82	CDEN, FC	0.80
	(3)	DDEN, FC, FL	0.86	CDEN, FC, FL	0.85
Tensile Index	(1)	DDEN	0.63	CDEN	0.67
	(2)	DDEN, FC	0.69	CDEN, FC	0.71
	(3)	DDEN, FL, R14	0.79	CDEN, FL, R14	0.80
Stretch	(1)	FC	0.55	FC	0.55
	(2)	DDEN, FC	0.69	CDEN, FC	0.67
	(3)	DDEN, FC, FL	0.72	CDEN, FC, FL	0.71
Burst Index	(1)	DDEN	0.63	CDEN	0.67
	(2)	DDEN, FC	0.70	CDEN, FC	0.72
	(3)	DDEN, FL, R14	0.82	CDEN, FL, R14	0.83
Tear Index	(1)	FL	0.56	FL	0.56
	(2)	DDEN, FL	0.85	CDEN, FL	0.84
	(3)	DDEN, FL, R14	0.89	CDEN, FL, R14	0.88

Table 11-12. Three Variable Prediction Equations Using Disk Density

Dependent Variable	Independent Variable Coefficients[1]					
	Intercept	DDEN	FC	FL	R14	R^2
Sheet density	902.8	-0.297	-0.520	-28.694		0.861
Tensile index	149.5	-0.110		-19.285	0.512	0.789
Stretch	4.58	-0.001	-0.004	-0.142		0.723
Burst index	12.1	-0.010		-1.794	0.050	0.824
Tear index	-38.5	0.065		8.605	0.153	0.889

1. valid for $319 \leq DDEN \leq 558$; $170 \leq FC \leq 269$; $2.39 \leq FL \leq 3.48$; $31.0 \leq R14 \leq 73.5$

Table 11-13. Three Variable Prediction Equations Using Chip Density

Dependent Variable	Independent Variable Coefficients[1]					
	Intercept	CDEN	FC	FL	R14	R^2
Sheet density	910.1	-0.325	-0.492	-29.915		0.847
Tensile index	153.6	-0.125		-17.801	0.469	0.795
Stretch	4.59	-0.001	-0.004	-0.149		0.707
Burst index	12.4	-0.011		-1.666	0.047	0.829
Tear index	-40.6	0.073		7.917	0.175	0.882

1. valid for $325 \leq CDEN \leq 534$; $170 \leq FC \leq 269$; $2.39 \leq FL \leq 3.48$; $31.0 \leq R14 \leq 73.5$

Table 11-14. Kraft Pulp Handsheet Properties after 1000 Revolutions in a PFI Mill Characteristic of Selected Utilization Options for 50-Year Rotation Douglas-Fir

Wood type[1] or Option	Sheet Density kg/m^3	Tensile Index $N \cdot m/g$	Tear Index $mN \cdot m^2/g$
Mature wood Option A Option C (separate)	550	68	30
Juvenile wood Option C (separate)	600	78	21
Option B	592	76	23
Option C (mixtures)	550 to 600	68 to 78	30 to 21
Top wood Option D	590	83	19

1. See text for definition of options

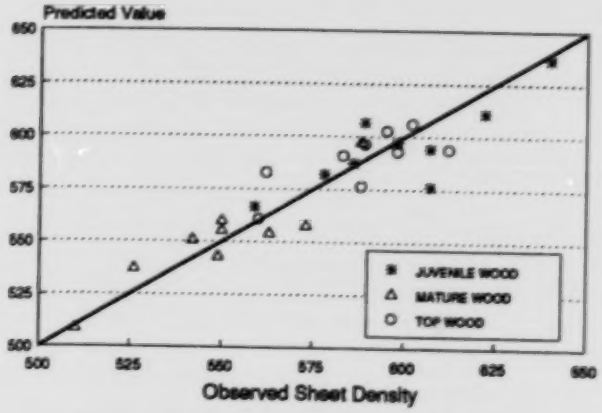


Fig. 11-28 Predicted versus observed sheet density values for kraft pulp handsheets

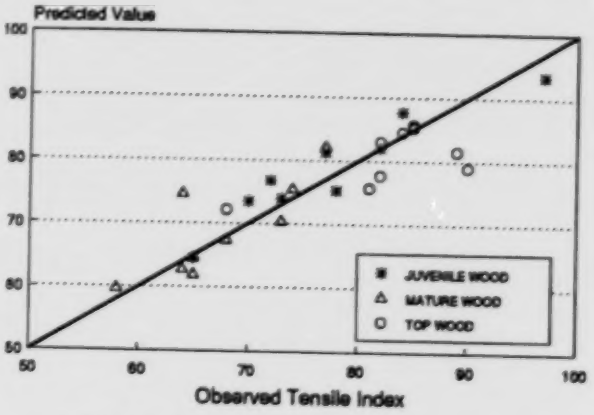


Fig. 11-29 Predicted versus observed tensile index values for kraft pulp handsheets

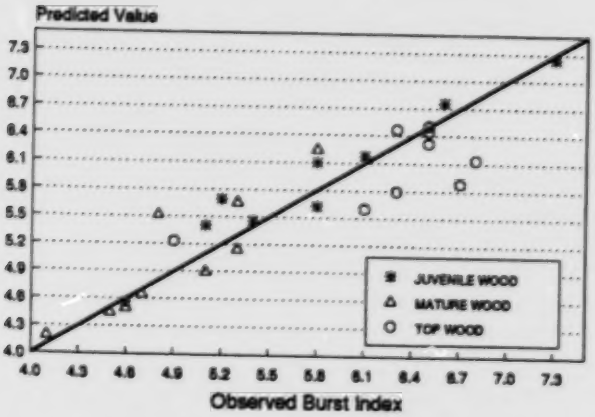


Fig. 11-30 Predicted versus observed burst values for kraft pulp handsheets

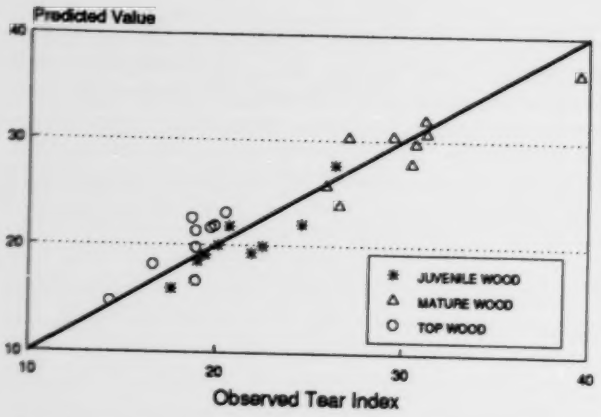


Fig. 11-31 Predicted versus observed tear index values for kraft pulp handsheets

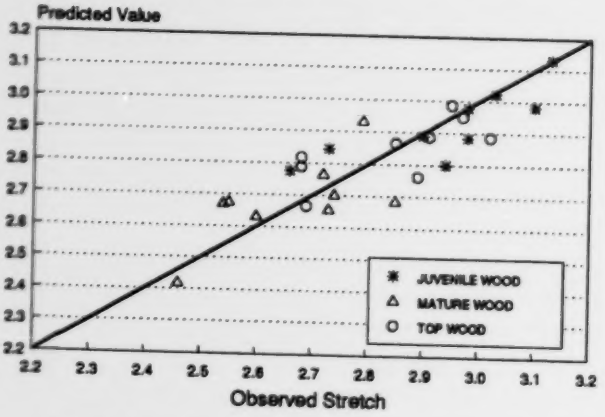


Fig. 11-32 Predicted versus observed stretch index values for kraft pulp handsheets

Summary and Conclusions

The pulping characteristics, yield, and handsheet physical properties of unbleached kraft pulps have been determined from second-growth Douglas-fir trees of low, medium and high density from three different sites on Vancouver Island. Evaluations were performed on representative samples of chips cut from juvenile wood, mature wood and top wood sections of each of the nine trees sampled.

The principal conclusions are as follows:

1. Yields of bleachable-grade kraft pulps (5 percent Klason lignin) were always lower for juvenile wood relative to those for mature wood from the same tree. Kraft pulp yields from top wood components were higher than those from their corresponding juvenile wood component. These trends reflect the wood chemistry differences reported in Chapter 10 and elsewhere.

2. Juvenile wood cooked faster than the corresponding mature wood component; top wood cooked faster than mature wood but slower than juvenile wood.

3. For a given tree, alkali requirements to cook to bleachable-grade pulps decreased in the order juvenile wood > mature wood > top wood, but the differences were small enough to be statistically insignificant at the 5 percent level.

4. Similar trends with respect to yield, cooking rate and alkali requirements were observed for linerboard-grade kraft pulps (15 percent Klason lignin).

5. The fiber length distributions of bleachable-grade kraft pulps from juvenile wood and top wood samples were similar. Kraft pulps from mature wood from a given site contained a higher proportion of long fibers.

6. The pith-to-bark weight-weighted fiber lengths of bleachable-grade kraft pulps increased rapidly across the juvenile wood and top wood zones, after which fiber lengths continued to increase throughout the mature wood section for some trees.

7. Fibers of bleachable-grade kraft pulps made from juvenile wood were consistently less coarse than those from their corresponding mature wood pulps, but there was no well defined relationship between coarseness and chip density between trees.

8. Within each tree, the weight-weighted fiber length of bleachable-grade kraft pulps increased in the order juvenile wood < top wood < mature wood, but there was no well defined relationship between weight-weighted fiber length and chip density between trees.

9. Within each tree, bleachable-grade kraft pulps from juvenile wood and top wood formed denser sheets than those from mature wood at any given level of beating or freeness, and were smoother and less porous to air.

10. Bleachable-grade kraft pulps from juvenile wood and top wood showed better interfiber bonding than those from mature wood pulps. Tensile and burst indexes, stretch and stress-strain factors were all larger than those from mature wood pulps, but the tear index was substantially lower.

11. Handsheet properties of all 27 bleachable-grade kraft pulps can be predicted and explained on a basis of wood or chip density, fiber length and fiber coarseness. Three variable models were good predictors of kraft pulp handsheet properties.

12. Consideration of available options for utilization of shorter rotation Douglas-fir for kraft pulps indicates that there is excellent potential for the production of kraft pulps with a wide range of properties suitable for many different end uses.

Acknowledgements

The authors gratefully acknowledge Ernie Hamm for providing the pith-to-bark fiber length data.

The authors also gratefully acknowledge the valuable technical assistance of Wai Gee, James Drummond, Alexandra Kwong, Barry Christie and Tim Stephens of the Resource Evaluation Section, Vancouver Laboratory, for sample procurement, preparation, kraft cooking and fiber characterization. The technical expertise of the Physical Testing Section, Pointe Claire Laboratory, in beating and handsheet evaluation is much appreciated -- as were the suggestions made by Dr. Raj Seth, Vancouver Laboratory, for handling the quantity of handsheet data obtained and for improving the text.

Finally, the patience and considerable efforts of Emil Koller, Pointe Claire Laboratory, in analyzing and consolidating the handsheet data, are gratefully appreciated. The authors are grateful to Jean Cook, Forintek Canada Corp. for undertaking the multiple linear regression analyses and for providing the associated text.

References

Bichard, W. and P. Scudamore. 1988. An evaluation of the comparative performance of the Kajaani FS-100 and FS-200 fiber length analyzers. Tappi J. 71(12):149-155.

Clark, J.d'A. 1970. Freeness fallacies and facts. Svensk Papperstid. 73(3):54-62.

Hatton, J.V. 1983. Process control: residual effective alkali/H factor relationships in kraft pulping. Pulp. Pap. Res. Inst. Can., PPR 421, Pointe Claire, Que.

Hatton, J.V. and M. Samkova. 1972. Relationship between bulk and handsheet physical properties for kraft pulps. I. Tree components of *Picea glauca*. Tappi 55(1):93-96.

Keays, J.L. and J.M. Bagley. 1970. Digester assembly for precision pulping studies. Tappi 53(10):1935-1940.

Kellogg, R.M. and E. Thykeson. 1975a. Predicting kraft mill paper strength from fiber properties. Tappi 58(4):131-135.

Kellogg, R.M., E. Thykeson and W.G. Warren. 1975b. The influence of wood and fiber properties on kraft converting-paper quality. Tappi 58(12):113-116.

Kellogg, R.M. and J.S. Gonzalez. 1976. Relationships between anatomical and sheet properties in western hemlock kraft pulps. Part II. Sheet property relationships. CPPA Trans. Tech. Sect. 2(3):72-77.

Kesler, R.B. 1966. Monitoring kraft pulp mill liquors for sulfide and effective alkali. Tappi 49(2):71-74.

Kibblewhite, R.P. 1980. Radiata pine corewood and slabwood, and their interrelationships with (kraft) pulp and handsheet properties. N. Z. J. For. Sci. 10(3):533-550.

Kibblewhite, R.P. 1982. Qualities of radiata pine papermaking fibers. Appita 35(4):289-298.

Kibblewhite, R.P. and J.A. Lloyd. 1983a. Interrelations between the wood, fiber, and kraft pulp properties of new-crop radiata pine 12-year-old thinnings. FRI Bull. (N. Z. For. Serv. For. Res. Inst.) No. 44. 19p.

Kibblewhite, R.P. and J.A. Lloyd. 1983b. Interrelations between the wood, fiber, and kraft pulp properties of new-crop radiata pine corewood and slabwood. FRI Bull. (N. Z. For. Serv. For. Res. Inst.) No. 45. 26p.

Kibblewhite, R.P. 1984a. *Pinus radiata* wood residue qualities and some utilization options. N. Z. J. For. Sci. 14(3):382-394.

Kibblewhite, R.P. 1984b. Radiata pine wood and kraft pulp quality relationships. Appita 37(9):741-747.

Matolcsy, G.A. 1975. Correlation of fiber dimensions and wood properties with the physical properties of kraft pulp of *Abies balsamea. L.* (Mill.). Tappi 58(4):136-141.

Semke, L.K. 1984. Effects of juvenile pine fibers on kraft paper properties. In: Proc. Symp. on utilization of the changing wood resource in the southern United States. June 12-14. Raleigh, NC. North Carolina State Univ. (1984). p.160-177.

Senft, J.F. and B.A. Bendtsen. 1985. Measuring microfibrillar angles using light microscopy. Wood and Fiber Science. 17(4):564-567.

Weisberg, S. 1980. Applied Linear Regression. John Wiley and Sons, New York. 283p.

CHAPTER 12

Refiner Mechanical Pulps

J.V. Hatton and S.S. Johal *Resource Evaluation Section, Pulp and Paper Research Institute of Canada*

Introduction

The yield and quality of unbleached kraft pulps from juvenile, mature and top wood having been described in Chapter 11, the properties of refiner mechanical pulps made from the same wood samples are presented in this Chapter.

Materials and Methods

Refiner Mechanical Pulping

Accept chips (as defined in Chapter 11) of the 27 samples of second-growth Douglas-fir were refined in a 30.5 centimeter, open-discharge, Sprout Waldron laboratory refiner using the following processing conditions:

Plate type	:	D2A507
Number of passes	:	2 to 4 depending upon freeness level
Plate gap, mm	:	0.5 to 0.6 (first pass); 0.05 to 0.15 (subsequent passes)
Refining consistency, %	:	18 to 22
Refining temperature, °C	:	92 to 98

Refining conditions were chosen to give pulp freenesses in the range from 50 to 200 milliliters Canadian Standard Freeness (Csf).

Chip solids contents ranged from a high of 77 percent od wood for juvenile wood samples to a low of 40 percent for the greenest top wood sample. To remove the effects of moisture content on these refining trials, juvenile wood and other samples drier than 60 percent solids were soaked in water at room temperature for 24 hours. Each sample was centrifuged to remove surface water and its final solids content determined.

Before each pass, the refiner was heated to 98°C with pressurized steam and the plate clearance set at zero. Chips (or pulp) were fed into the refiner by a vibratory feeder, and the pulps were dewatered through a 250-mesh stainless steel screen. Following each final pass, latency was removed by disintegrating a pulp for five minutes in boiling water in a British standard disintegrator. Each pulp was screened on a 6-cut laboratory flat screen equipped with white water recirculation. Screen rejects and Bauer-McNett fiber classications on screened pulps were determined. Handsheets were made and tested for structural, mechanical and optical properties using standard methods.

Statistical Analysis

Two different statistical approaches were used for data analysis. In the first, refiner mechanical pulping data were standardized by interpolation (or extrapolation) to given levels of pulp freeness, sheet density and specific energy consumption, after which paired difference analysis was carried out. This method allows determination of the statistical significance of differences between refiner mechanical pulp properties from the three different tree components. A two-tailed t-test was used throughout. This method does not anticipate the algebraic sign of the mean difference for each pair and is more conservative than the one-tailed test. Following the standardization of data, the second approach was to carry out multiple linear regression analyses using the six handsheet properties of sheet density, tensile index, stretch, burst index, tear index and scattering coefficient as dependent variables, and the six wood and fiber properties of disk density, chip density, weight-weighted fiber length, zero span, R-48 fraction and Klason lignin in wood as independent variables. The objective of these analyses is to develop prediction equations for bulk, strength and optical properties of refiner mechanical pulp handsheets with measured fiber characteristics produced from wood of a given density.

The means, standard deviations, minima and maxima of the 27 values for each variable were computed. Prediction equations developed from these data are not valid for future values of the independent variables outside the range of these data.

The correlation coefficient was computed for each pair of variables and tests for significant linear correlation were performed. These tests are useful for pairs of dependent variables because significant linear correlations between any two variables (i.e., $r \geq 0.99$) could allow one handsheet property to be determined from another. They are useful for pairs of independent variables because significant linear correlations between any two variables, one of which is included in a prediction equation, would suggest that inclusion of the other variable in the equation would be unlikely to produce an equation with improved predictive power.

Linear prediction equations for each dependent variable were developed using the available independent variables. In each case, the "best" one, two and three independent variable

models were first computed. "Best" was defined as that combination of independent variables which gave the highest R^2 for a given number of independent variables. Whenever an additional variable was added to the equation an F-test was performed to determine whether the new variable added significantly to the regression (Weisberg, 1980). In some cases, linear relationships did not produce satisfactory prediction equations with three variables. In those cases all five variables were tried and, if a linear model was still not appropriate, an effort was made to find an alternate model. Finally, the predicted values versus observed values for the chosen predictive models were plotted for each dependent variable.

Results and Discussion

From the 27 chip samples used, a total of 72 refiner mechanical pulps were produced, two from each of the Ladysmith samples and three from each of the Lizard Lake and Jordan River samples.

Handsheets were made and tested and the complete data sets (the raw data) are shown in Tables 12-1, 12-2 and 12-3 for Ladysmith, Lizard Lake and Jordan River, respectively.

In general, the development of the sheet properties of mechanical pulps can be described using a given level of pulp freeness, sheet density, or specific energy as a yardstick. Thus, to facilitate data analysis and discussion, the raw data were adjusted to a freeness of 100 milliliters Csf (Table 12-4), a sheet density of 320 kilograms per cubic meter (Table 12-5), and a specific energy of 10.5 megajoules per kilogram (Table 12-6). These standardized data were then statistically analyzed using the two approaches described earlier.

Energy Consumption

The energy consumed to reach a given level of freeness is shown in Figure 12-1. The raw data show an appreciable scatter because of between-tree differences, but there is some indication that juvenile wood required more energy than either mature wood or top wood to reach a given freeness. This was confirmed by the statistical analysis shown in Table 12-7 which summarizes within-tree differences. However, the energy difference for the mature wood-top wood pair was not significant. Since the mean chip density of mature wood samples exceeds that of top wood by an amount greater than that by which it exceeds juvenile wood samples (see Chapter 10), the role of chip density must be properly evaluated. The specific energies required to refine chips to 100 milliliters Csf are plotted versus chip density in Figure 12-2. The energy required by mature wood samples, as expected, was higher than that for top wood samples at a given chip density value below 415 kilograms per cubic meter. However, the energy required for a given tree component to reach a freeness of 100 milliliters Csf decreased with increasing chip density, which was unexpected. The three regression equations which describe this trend are somewhat inconclusive because of the relatively low values of their coefficients of determination (r^2).

Juvenile Wood
Specific energy, MJ/kg = 16.15 - 0.0107 (Chip density); $r^2 = 0.51$

Mature Wood
Specific energy, MJ/kg = 19.70 - 0.0188 (Chip density); $r^2 = 0.52$

Top Wood
Specific energy, MJ/kg = 21.02 - 0.0261 (Chip density); $r^2 = 0.58$.

Fiber morphology (which affects chip density) rather than chip density *per se*, may be the controlling factor in specific energy requirements in refining. Some confirmation of this conclusion is afforded by the fact that, in the chip density range from 375 to 475 kilograms per cubic meter, the energy requirements for juvenile wood and mature wood samples were similar for a given value of chip density (Figure 12-2) but the key mechanical and optical properties were different for the two wood types (Table 12-6). Similar inconsistencies between energy consumption, wood type and wood density were observed by Corson (1984) in his work on *Pinus radiata* refiner mechanical and thermomechanical pulps.

The implications of the present study are that future, managed stands would most likely contain larger amounts of juvenile wood with lower average wood density than presently available. This wood will require a higher specific energy than at present to reach a given freeness, and will have mechanical and optical properties different from those of mature wood with similar density.

Fiber Size Distribution

The long-fiber fraction (R-48) retained on the 48-mesh screen of a Bauer-McNett fiber classifier decreased with decreasing freeness, as shown in Figure 12-3. At a given freeness, R-48 was higher for mature wood samples. This is shown in Table 12-7. The R-48 values also decreased with increasing specific energy consumption, Figure 12-4. The long-fiber fraction is plotted versus weight-weighted fiber length in Figure 12-5, and it can be seen that, despite the expected correlation, there was a high degree of scatter in the data. Mature wood pulp data points were clustered to high values of weight-weighted fiber length, in contrast to those from juvenile wood and top wood pulps, which were clustered to lower weight-weighted fiber length values.

Much less variation was observed for the fines contents (P-200 fraction) of refiner mechanical pulps from the different samples. Fines contents decreased in the order, juvenile wood > mature wood > top wood, with their means and standard deviations of 27.9 (1.0), 26.3 (1.3) and 24.7 (2.1) percent, respectively. There was no apparent relationship between the long fiber and fines contents of the pulps examined.

Sheet Consolidation

The development of sheet density with freeness and specific energy is shown in Figures 12-6 and 12-7, respectively. Sheet density increased with decreasing freeness, and there was some indication that mature wood pulps gave denser sheets than did top wood pulps at a given freeness (Table 12-7). The corresponding trend with specific energy was less clear, but the analysis confirmed that mature wood pulps gave denser sheets than did both juvenile wood and top wood pulps at the same energy input (Table 12-9).

Tensile Strength

Tensile index increased with decreasing freeness (Figure 12-8), increasing sheet density (Figure 12-9) and increasing specific energy (Figure 12-10), as expected. At a given freeness or specific energy, the tensile indexes of mature wood pulps were always higher than those of juvenile wood pulps (Tables 12-4, 12-6, 12-7 and 12-9), but the magnitude of these differences was smaller as a function of freeness. Similar trends were present, but less evident, for tensile index as a function of sheet density (Tables 12-5 and 12-8).

Tearing Resistance

The tear indexes of refiner mechanical pulps from mature wood samples were consistently higher than those of juvenile wood or top wood pulps, regardless of whether the comparison was made on a basis of fiber length (Figure 12-11), freeness (Figure 12-12), sheet density (Figure 12-13), or specific energy (Figure 12-14). Similarly, the tear indexes of top wood pulps were consistently lower than those of juvenile wood pulps at a given freeness, sheet density, or specific energy (Tables 12-4, 12-5, 12-6, 12-7, 12-8 and 12-9).

The impressively larger tear indexes of mature wood pulps compared with juvenile wood or top wood pulps at a given value of tensile index are shown in Figure 12-15. The two well defined clusters of points for mature wood pulps at higher tear values, and those for juvenile wood and top wood pulps at lower tear values indicate, also, that the tear indexes of these pulps are essentially independent of tensile strength within the freeness range covered.

Optical Properties

High values of scattering coefficient and printing opacity are characteristic of refiner mechanical pulps produced from non-chemically treated chips, and are important for the use of such pulps in newsprint and other wood-containing printed papers. The scattering coefficients of mature wood pulps were lower than those from juvenile wood pulps at a given freeness (Figure 12-16), sheet density (Figure 12-17) or specific energy (Figure 12-18) as shown by the analyses reported in Tables 12-7, 12-8 and 12-9. In general, the scattering coefficients of mature wood pulps were lower than those from top wood pulps as well, but the magnitude and significance of this effect depended on the basis of comparison used (Tables 12-7, 12-8 and 12-9).

Scattering coefficients increased with tensile index (Figure 12-19). The much higher scattering of juvenile wood pulps relative to mature wood pulps at a given value of tensile index is clearly evident. The scattering of top wood pulps more closely resembled that of mature wood pulps.

The brightnesses of mature wood and top wood pulps were consistently higher than those of juvenile wood pulps from a given tree (Table 12-7).

Effects of Wood Density and Fiber Properties on Sheet Properties

In planning the new forest, or in preparation for utilization of second-growth stands, it is important that the effects of wood density and fiber properties on pulp properties be identified and quantified for the same reasons outlined in Chapter 11. In that chapter, it was shown that the wide ranging properties of kraft pulp handsheets made from 27 samples ranging widely in wood density could be predicted and explained on a basis of wood or chip density, fiber length and fiber coarseness.

A similar approach has been taken with the 27 refiner mechanical pulps from second-growth Douglas-fir whose sheet properties were adjusted to a freeness of 100 milliliters Csf, a sheet density of 320 kilograms per cubic meter, and a specific energy of 10.5 megajoules per kilogram.

The summary statistics from the data used to develop the prediction equations are shown in Table 12-10. The broad ranges observed for each variable suggest that prediction equations involving these variables should be widely applicable to the future Douglas-fir resource and provide much needed data for the PULPSIM model for this species.

The correlation coefficients (r) for each pair of variables are shown in Table 12-11 for data at a freeness of 100 milliliters Csf only. Values of r for data at a sheet density of 320 kilograms per cubic meter and a specific energy of 10.5 megajoules per kilogram are similar to those in Table 12-11 and have been omitted. Among dependent variables, tensile index and burst index were highly correlated ($r = 0.88$), as shown for kraft pulps in Chapter 11. Among independent variables, disk density and chip density were highly correlated ($r = 0.99$), as shown in Chapter 10. Thus, in the development of prediction equations, separate equations were developed for chip and disk densities. The former will be appropriate for future quality control purposes during the pulping process, while the latter will be more appropriate when it is required to predict the properties of handsheets manufactured from refiner mechanical pulps from trees for which disk densities are available. Other significant relationships between pairs of independent variables, and pairs of dependent versus independent variables, are evident from Table 12-11. In particular, fiber length and tear index, and Klason lignin and scattering coefficient, are highly correlated ($r = 0.85$).

Prediction equations were initially computed for each handsheet property using the best one to five variables as described earlier. Neither sheet density nor stretch could be adequately predicted using a linear combination of the independent variables. Even when density plus the other four independent variables were included in the model, the R^2 values for sheet density and stretch were no larger than 0.46 and 0.50, respectively, based on data at a freeness of 100 milliliters Csf.

The best two to five variable prediction equations chosen as models from this analysis are shown in Tables 12-12, 12-13 and 12-14 for handsheet properties at a freeness of 100 milliliters Csf, a sheet density of 320 kilograms per cubic meter and a specific energy of 10.5 megajoules per kilogram, respectively.

Values of R^2 for the handsheet properties of tear index and scattering coefficient were high irrespective of the basis chosen for comparison. These two dependent variables gave excellent plots of predicted versus observed values at constant freeness and constant specific energy, as shown in Figures 12-20 to 12-23. The rather significant influence of Klason lignin in wood on the scattering coefficients of refiner mechanical pulps from second-growth Douglas-fir requires further study.

Options for Utilization of Shorter Rotation Douglas-Fir

Future forest crops under some degree of management will be harvested in rotations shorter than those presently used. This change will likely bring about an increase in the ratio of juvenile to mature wood in a tree depending upon the relative growth rates of each wood type and the age of the tree at harvest. In the present study, and based on a total of 60 trees (10 trees from each of six sites), the amount of juvenile wood in a stem, i.e., from the butt to the unmerchantable top, was determined to be 49 percent for Douglas-fir trees with a mean age of 50 years (Chapter 1).

Four potential utilization options were considered to illustrate the effects of juvenile wood in the kraft pulping of second-growth Douglas-fir (Chapter 11). The same options are considered here to illustrate the specific effects of juvenile wood relative to mature wood in refiner mechanical pulping.

Thus, values of specific energy, sheet density, tensile index, tear index, and scattering coefficient for refiner mechanical pulps at a freeness of 100 milliliters Csf are shown in Table 12-15 for juvenile wood, mature wood and top wood, and the four utilization options.

The use of increasing quantities of juvenile wood (including thinnings) affects the tensile and tearing strengths as for kraft pulps (see Chapter 11), but the magnitudes of these changes are smaller for mechanical pulps. Specific energy requirements can be expected to increase by about 5 percent, but this could be offset by the superior scattering coefficients given by juvenile wood relative to mature wood.

Summary and Conclusions

Fibers from mature wood refiner mechanical pulps were longer and coarser than those from juvenile wood and top wood pulps. As a result, handsheets made from mature wood pulps were stronger than those from juvenile wood and top wood pulps, as shown by their superior tensile and tearing strengths at a given pulp freeness, sheet density, or specific energy consumption. The optical properties of mature wood pulps, however, were inferior, as shown by decreased printing opacity and scattering coefficient, compared to those of juvenile wood and mature wood pulps. The brightness of mature wood pulps was low, but consistently higher than that of juvenile wood pulps. The effect of chip density is still not well understood. Although mature wood samples, with their longer and coarser fibers and higher density than juvenile wood and top wood samples, required more energy to reach a given freeness, the energy requirements for a given tree component decreased as the chip density increased. The implications of the present study are that future, managed stands will probably contain larger amounts of juvenile wood with lower average wood density than presently available. This wood will require a higher specific energy than used at present to reach a given freeness, and will have mechanical and optical properties different from those of mature wood with similar density. This trend needs to be better understood so that appropriate action can be taken to facilitate the planning of Canada's second-growth forests. Handsheet properties of all 27 refiner mechanical pulps can be predicted and explained primarily on a basis of fiber length, fiber strength and Klason lignin in wood. Density is important but, unlike the models developed for kraft pulps, plays a less dominant role. Consideration of available options for utilization of shorter rotation Douglas-fir refiner mechanical pulps suggests that there is potential for the production of mechanical pulps with a range of mechanical and optical properties. However, the color problems (Chapter 10) and low brightness of these pulps must first be overcome before mechanical pulping of this species is practical on a commercial scale.

Acknowledgements

The authors are indebted to Emil Koller, Pointe Claire Laboratory, for consolidating the handsheet data and for providing 19 of the figures shown in the text. Advice on statistical procedures by Bruce Allison, Vancouver Laboratory, is much appreciated. The authors are grateful to Jean Cook, Forintek Canada Corp. for undertaking the multiple linear regression analyses and for providing the associated text.

References

Corson, S.R. 1984. Influence of wood quality characteristics on TMP and RMP from New Zealand-grown radiata pine. Appita 37(5):400-408.

Weisberg, S. 1980. Applied Linear Regression. John Wiley and Sons. New York. 283p.

Table 12-1. Properties of Refiner Mechanical Pulps from Second-Growth Douglas-Fir (Site: Ladysmith)

Tree No.	Wood Sample	Specific Refining Energy MJ/kg	Csf ml	Sheet Density kg/m^3	Sheffield Roughness	Air Resistance s/100 ml	Tensile Index N·m/g	Stretch %	Zero Span Breaking Length km	Stress-Strain Factor mJ/g	Burst Index kPa·m^2/g	Tear Index mN·m^2/g	Brightness %	Printing Opacity %	Scattering Coefficient cm^2/g
7	JW	12.6	62	369	206	99	45	2.12	12.4	628	2.6	8.5	42.8	99.2	578
		10.3	147	315	265	19	35	1.87	11.8	432	1.9	8.9	41.4	98.6	508
	MW	11.1	83	344	NA[1]	46	41	1.72	12.4	464	2.3	8.7	50.8	96.2	481
		8.6	142	299	328	13	37	1.81	11.3	438	1.9	9.6	49.3	95.4	439
	TW	11.8	77	323	284	47	41	1.79	11.2	473	2.3	7.0	49.0	97.3	511
		10.4	155	285	331	10	33	1.69	10.7	366	1.7	7.0	48.6	95.9	464
2	JW	13.1	74	334	222	51	38	2.03	11.3	511	2.0	7.0	40.1	99.4	630
		10.5	140	312	278	20	30	1.60	11.1	310	1.5	6.9	37.5	99.4	562
	MW	11.9	58	356	231	86	41	1.87	12.9	500	2.3	8.1	47.8	98.2	561
		10.1	116	311	279	22	34	1.77	11.9	398	1.8	8.2	46.9	97.5	497
	TW	12.2	64	326	276	43	35	1.69	9.6	380	1.8	5.7	45.2	98.2	526
		9.5	129	287	334	11	27	1.52	10.2	266	1.4	5.7	44.2	97.6	482
9	JW	12.5	72	339	214	63	36	1.93	10.5	464	1.8	5.8	42.4	99.4	664
		9.7	158	288	298	13	25	1.67	10.0	286	1.2	5.1	41.0	99.1	577
	MW	12.7	71	334	257	49	38	1.90	11.0	476	2.0	7.0	49.3	97.6	548
		9.7	180	279	355	7	27	1.58	10.6	282	1.3	7.0	48.1	96.8	472
	TW	10.5	80	329	257	38	34	1.64	9.7	362	1.5	4.8	50.1	97.7	580
		7.5	151	266	352	7	20	1.30	8.7	171	0.9	4.0	48.0	97.3	507

1. NA = not available

Table 12-2. Properties of Refiner Mechanical Pulps from Second-Growth Douglas-Fir (Site: Lizard Lake)

Tree No.	Wood Sample	Specific Refining Energy MJ/kg	Csf ml	Sheet Density kg/m^3	Sheffield Roughness	Air Resistance s/100 ml	Tensile Index N·m/g	Stretch %	Zero Span Breaking Length km	Stress-Strain Factor mJ/g	Burst Index kPa·m^2/g	Tear Index mN·m^2/g	Brightness %	Printing Opacity %	Scattering Coefficient cm^2/g
9	JW	11.5	79	330	250	32	31	2.24	11.0	457	1.7	7.3	29.9	99.5	533
		9.7	144	289	338	7	23	2.03	10.9	314	1.2	6.2	30.6	99.4	487
		8.5	170	275	370	4	20	1.71	10.1	225	1.0	5.3	29.1	99.0	473
	MW	9.7	78	340	304	49	34	2.20	11.5	502	2.0	8.1	36.6	99.4	513
		8.6	113	299	350	15	28	1.87	10.6	341	1.6	8.3	33.3	99.0	462
		8.2	208	270	363	4	22	1.83	10.4	268	1.1	7.3	31.6	98.8	420
	TW	11.0	78	352	229	52	34	1.95	11.3	431	1.8	6.3	35.9	99.0	511
		8.6	138	278	344	8	25	1.58	10.1	247	1.2	6.0	36.2	98.2	466
		8.3	169	306	330	8	24	1.59	10.0	245	1.2	5.8	33.4	98.6	443
7	JW	13.2	58	347	251	80	37	2.04	11.7	495	2.0	7.1	30.3	99.6	549
		10.8	115	311	286	20	29	1.82	10.3	350	1.5	6.8	30.6	99.3	500
		9.5	171	274	346	6	24	1.74	9.8	276	1.2	6.6	31.6	98.9	451
	MW	13.8	67	350	242	81	40	2.09	11.4	554	2.2	8.7	37.6	98.7	488
		11.3	132	313	283	23	32	1.83	11.0	376	1.7	8.2	38.4	97.9	436
		9.6	186	290	355	9	27	1.73	11.2	309	1.4	8.6	39.1	97.2	402
	TW	12.9	70	338	360	68	40	1.98	10.1	472	2.0	6.4	40.6	98.2	496
		10.4	120	292	310	19	32	1.76	9.5	361	1.6	6.5	40.4	97.8	453
		10.4	130	305	307	16	31	1.64	9.5	328	1.5	6.4	37.0	98.1	451
5	JW	14.4	70	382	164	122	39	2.14	11.0	561	2.2	7.3	32.3	99.5	534
		11.9	124	314	258	25	31	1.88	10.9	380	1.6	7.3	35.8	98.9	493
		10.6	132	341	236	27	31	1.90	10.9	388	1.6	7.3	34.1	99.3	492
	MW	15.0	72	383	175	139	43	2.12	11.6	599	2.4	8.4	37.3	99.1	497
		11.4	111	330	243	41	36	1.97	10.9	469	2.0	8.4	38.5	98.5	461
		10.0	205	327	285	13	30	1.65	10.9	323	1.5	8.1	39.2	97.5	426
	TW	14.6	69	361	228	132	40	1.80	11.6	462	2.1	6.6	39.2	98.6	487
		12.5	103	355	206	61	35	1.66	10.2	376	1.8	6.7	39.3	98.2	476
		11.2	137	299	293	21	30	1.60	10.3	308	1.4	6.6	38.7	97.9	451

Table 12-3. Handsheet Properties of Refiner Mechanical Pulps from Second-Growth Douglas-Fir (Site: Jordan River)

Tree No.	Wood Sample	Specific Refining Energy MJ/kg	Csf ml	Sheet Density kg/m^3	Sheffield Roughness	Air Resistance s/100 ml	Tensile Index N·m/g	Stretch %	Zero Span Breaking Length km	Stress-Strain Factor mJ/g	Burst Index kPa·m^2/g	Tear Index mN·m^2/g	Brightness %	Printing Opacity %	Scattering Coefficient cm^2/g
6	JW	11.3	94	313	255	25	32	2.36	10.5	512	1.8	7.8	37.7	99.1	560
		10.0	154	282	348	6	25	2.01	10.7	336	1.3	6.4	37.0	98.4	497
		9.0	194	280	363	4	23	1.94	11.1	299	1.2	6.1	38.6	98.0	476
	MW	10.3	114	321	295	16	32	2.03	11.5	437	1.9	8.7	39.5	98.1	479
		9.8	141	299	330	8	32	2.04	11.2	438	1.7	8.8	42.1	97.4	457
		8.6	199	272	369	3	27	1.92	11.4	344	1.5	8.4	43.4	96.0	416
	TW	12.3	74	307	302	41	36	1.96	10.2	464	1.8	6.4	37.1	98.5	491
		10.5	117	299	302	18	31	1.80	9.8	361	1.6	6.7	38.5	97.9	459
		7.4	169	265	367	5	24	1.65	10.0	260	1.2	5.8	35.2	98.0	433
2	JW	12.4	75	331	235	48	35	2.27	11.2	539	2.0	7.8	37.7	99.0	544
		9.8	156	287	330	9	26	1.98	10.7	344	1.4	7.1	38.8	98.5	483
		7.3	174	292	334	7	25	1.85	10.9	303	1.3	7.0	40.0	98.0	471
	MW	10.3	69	370	213	85	40	2.33	12.0	636	2.3	8.2	35.6	99.4	544
		8.2	151	301	304	13	31	1.98	10.6	407	1.7	9.1	39.3	98.2	447
		6.5	196	292	335	7	28	1.87	11.2	353	1.5	9.0	37.6	97.6	421
	TW	10.6	91	337	233	48	37	2.01	10.8	490	1.9	6.8	38.3	98.5	508
		8.6	134	300	308	15	30	1.76	10.5	342	1.6	6.9	38.9	97.9	466
		7.4	137	302	305	17	31	1.77	10.3	352	1.6	6.5	39.0	98.0	NA[1]
8	JW	13.3	93	323	238	43	33	2.16	10.6	471	1.8	7.2	34.6	99.4	556
		10.8	117	304	273	25	31	2.04	10.6	413	1.6	7.1	37.1	99.0	529
		10.6	168	279	338	8	25	1.90	10.6	308	1.3	6.6	33.4	99.2	483
	MW	13.1	82	338	249	78	40	2.13	11.3	559	2.4	9.0	37.7	98.9	505
		10.7	144	296	302	19	33	1.99	10.7	422	1.8	9.4	37.3	98.4	460
		9.0	206	281	346	7	29	1.84	11.5	348	1.6	8.9	39.9	97.3	434
	TW	12.3	75	324	270	75	39	2.08	10.4	526	2.1	6.9	36.4	98.7	507
		8.9	127	289	313	20	32	1.99	10.4	419	1.7	7.2	37.8	98.3	475
		8.3	198	270	364	5	27	1.75	9.9	301	1.3	6.4	37.8	97.8	431

1. NA = not available

Table 12-4. Refiner Mechanical Pulp Properties of Second-Growth Douglas-Fir at a Canadian Standard Freeness (ml Csf)of 100 Milliliters

Tree No.	Wood Sample	Specific Refining Energy MJ/kg	Weight-Weighted Fiber Length (WWFL) mm	R-48 Fraction[1] %	Sheet Density kg/m^3	Sheffield Roughness	Air Resistance s/100 ml	Tensile Index N-m/g	Stretch %	Zero Span Breaking Length km	Burst Index kPa-m^2/g	Tear Index mN-m^2/g	Brightness %	Printing Opacity %	Scattering Coefficient cm^2/g
Ladysmith															
7	JW	11.6	2.11	56.8	345	232	63	40	2.01	12.09	2.3	8.7	42.2	98.9	547
	MW	10.4	2.11	58.2	331	288	36	40	1.75	12.09	2.2	8.9	50.4	96.0	469
	TW	11.4	1.95	58.1	312	298	36	39	1.76	11.05	2.1	7.0	48.9	96.9	497
2	JW	12.1	1.98	51.4	325	244	39	35	1.86	11.21	1.8	7.0	39.1	99.4	603
	MW	10.6	2.02	55.3	323	266	39	36	1.80	12.16	2.0	8.1	47.2	97.7	515
	TW	10.7	1.81	51.9	304	308	25	31	1.60	9.91	1.6	5.7	44.7	97.9	502
9	JW	11.6	1.77	50.3	322	241	47	33	1.85	10.36	1.6	5.6	41.9	99.3	636
	MW	11.9	2.13	55.2	319	283	37	35	1.81	10.85	1.9	7.0	49.0	97.4	528
	TW	9.7	1.63	47.7	311	284	29	30	1.54	9.37	1.3	4.6	49.5	97.6	559
Lizard Lake															
9	JW	10.9	1.82	56.0	317	278	24	29	2.17	10.99	1.5	6.9	30.1	99.5	518
	MW	9.0	2.27	56.2	314	333	28	30	1.99	10.91	1.7	8.2	34.1	99.2	481
	TW	10.1	1.92	56.2	325	271	36	31	1.81	10.82	1.6	6.2	36.0	98.7	495
7	JW	11.4	2.02	54.5	320	277	36	32	1.88	10.67	1.6	6.9	30.5	99.4	513
	MW	12.5	2.21	59.4	331	263	51	36	1.96	11.19	2.0	8.4	38.0	98.3	462
	TW	11.4	1.69	57.5	310	330	38	35	1.85	9.72	1.8	6.4	40.4	98.0	470
5	JW	13.0	2.05	54.7	344	216	68	35	2.00	10.95	1.8	7.3	34.2	99.2	511
	MW	12.4	2.11	58.2	345	224	69	38	2.01	11.06	2.1	8.4	38.2	98.7	471
	TW	12.7	1.97	57.0	356	208	67	36	1.67	10.33	1.8	6.7	39.3	98.2	477
Jordan River															
6	JW	11.2	1.88	52.0	310	264	23	31	2.32	10.51	1.7	7.7	37.6	99.0	554
	MW	10.6	2.10	56.1	332	277	20	32	2.02	11.64	2.0	8.6	38.1	98.5	490
	TW	11.2	1.88	54.6	302	302	27	33	1.86	9.96	1.7	6.6	37.9	98.1	472
2	JW	11.6	2.04	54.4	317	264	36	32	2.18	11.07	1.8	7.6	38.0	98.9	525
	MW	9.5	2.23	56.4	344	247	57	37	2.20	11.46	2.1	8.5	37.0	99.0	507
	TW	10.2	1.94	54.9	329	249	41	36	1.96	10.71	1.9	6.8	38.4	98.4	499
8	JW	12.6	1.92	53.2	317	248	38	32	2.12	10.55	1.8	7.2	35.4	99.3	548
	MW	12.4	2.28	57.9	326	264	61	38	2.09	11.15	2.2	9.1	37.6	98.8	492
	TW	10.7	2.01	55.1	307	291	48	35	2.04	10.43	1.9	7.1	37.1	98.5	492

1. Retained on 48 mesh screen of Bauer-McNett fiber classifier

Table 12-5. Refiner Mechanical Pulp Properties of Second-Growth Douglas-Fir at a Sheet Density of 320 Kilograms per Cubic Meter (kg/m^3)

Tree No.	Wood Sample	Csf ml	Tensile Index N·m/g	Burst Index $kPa \cdot m^2/g$	Tear Index $mN \cdot m^2/g$	Printing Opacity %	Scattering Coefficient cm^2/g
Ladysmith							
7	JW	139	36	2.0	8.8	98.7	515
	MW	114	39	2.1	9.2	95.8	459
	TW	83	41	2.2	7.0	97.2	507
2	JW	116	33	1.7	6.9	99.4	587
	MW	104	36	1.9	8.1	97.6	510
	TW	74	34	1.7	5.7	98.1	519
9	JW	104	32	1.6	5.6	99.3	632
	MW	99	35	1.9	7.0	97.4	529
	TW	90	32	1.4	4.7	97.6	570
Lizard Lake							
9	JW	95	29	1.6	7.0	99.4	522
	MW	98	31	1.8	8.2	99.2	487
	TW	121	30	1.5	6.2	98.7	478
7	JW	100	32	1.6	6.9	99.4	512
	MW	124	34	1.8	8.6	98.0	446
	TW	96	36	1.8	6.4	98.0	477
5	JW	130	32	1.6	7.3	99.1	492
	MW	118	34	1.9	8.1	97.7	454
	TW	120	33	1.6	6.6	98.1	460
Jordan River							
6	JW	90	34	1.8	8.1	99.4	577
	MW	115	32	1.9	8.7	98.1	478
	TW	60	39	1.9	6.3	98.7	500
2	JW	100	33	1.8	7.6	98.8	530
	MW	140	33	1.8	8.8	98.5	470
	TW	114	34	1.8	6.8	98.2	489
8	JW	90	33	1.8	7.1	99.3	550
	MW	110	37	2.1	9.0	98.6	483
	TW	80	37	2.0	6.8	98.7	503

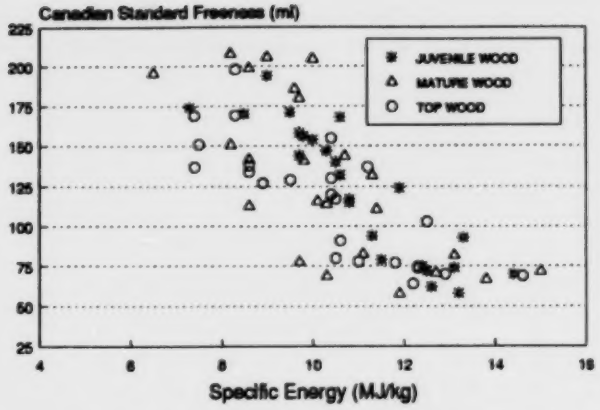


Fig. 12-1 Canadian standard freeness versus specific energy consumed

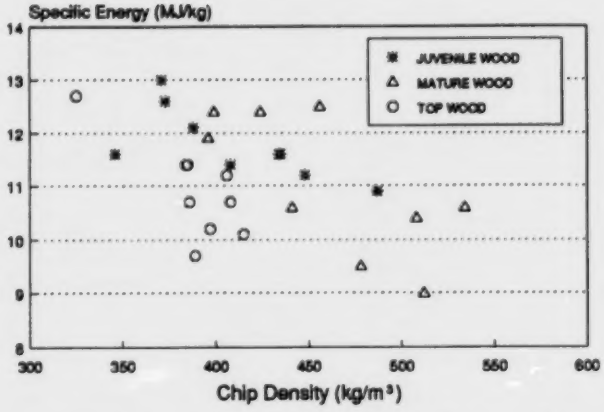


Fig. 12-2 Specific energy required to produce refiner mechanical pulps at 100 ml Csf versus chip density

Table 12-6. Refiner Mechanical Pulp Properties of Second-Growth Douglas-Fir at a Specific Energy of 10.5 Megajoules per Kilogram (MJ/kg)

Tree No.	Wood Sample	Csf ml	R-48 Fraction %	Sheet Density kg/m^3	Tensile Index N•m/g	Burst Index $kPa•m^2/g$	Tear Index $mN•m^2/g$	Printing Opacity %	Scattering Coefficient cm^2/g
Ladysmith									
7	JW	140	59.7	320	36	2.0	8.8	98.7	514
	MW	97	57.9	333	40	2.2	8.9	96.0	471
	TW	150	59.5	288	34	1.7	7.0	96.0	467
2	JW	140	53.7	312	30	1.5	6.9	99.4	562
	MW	103	55.5	321	36	1.9	8.1	97.7	511
	TW	104	52.3	301	30	1.6	5.7	97.8	498
9	JW	133	52.4	303	29	1.4	5.3	99.2	602
	MW	151	57.4	294	30	1.5	7.0	97.0	492
	TW	80	47.9	329	34	1.5	4.8	97.7	580
Lizard Lake									
9	JW	112	56.8	309	27	1.4	6.7	99.4	510
	MW	53	52.3	377	40	2.3	8.0	99.7	550
	TW	90	55.2	337	32	1.7	6.2	98.9	498
7	JW	135	58.1	298	28	1.4	6.8	99.2	489
	MW	158	62.1	302	30	1.6	8.4	97.6	420
	TW	128	59.2	301	32	1.6	6.4	98.0	453
5	JW	133	56.5	343	31	1.6	7.2	99.3	491
	MW	170	62.9	328	32	1.7	8.2	97.9	438
	TW	148	61.0	280	26	1.2	6.5	97.7	437
Jordan River									
6	JW	130	53.5	292	28	1.4	7.0	98.7	525
	MW	105	56.5	323	33	1.9	8.9	98.3	485
	TW	117	55.7	299	31	1.6	6.7	97.9	459
2	JW	122	58.4	304	28	1.5	7.3	98.6	509
	MW	66	53.4	368	41	2.3	8.0	99.5	542
	TW	96	54.6	337	37	1.9	6.8	98.4	506
8	JW	170	58.0	277	25	1.3	6.6	99.3	480
	MW	151	60.0	294	32	1.8	9.3	98.3	457
	TW	130	56.6	303	35	1.8	7.1	98.5	490

Table 12-7. Paired Statistical Analysis of Refiner Mechanical Pulp Properties at a Canadian Standard Freeness (ml Csf) of 100 Milliliters

Pulp Property	Test Pair	Mean Difference	Standard Deviation	Level of Significance[1]
Specific refining energy, MJ/kg	JW-MW	0.74	1.05	*
	JW-TW	0.88	0.79	**
	MW-TW	0.14	1.22	ns
Weight-weighted fiber length (WWFL), mm	JW-MW	-0.21	0.16	***
	JW-TW	0.09	0.14	**
	MW-TW	0.30	0.14	****
R-48 fraction, %	JW-MW	-3.29	1.70	****
	JW-TW	-1.08	1.70	*
	MW-TW	2.21	2.27	**
Sheet density, kg/m^3	JW-MW	-5.33	13.12	ns
	JW-TW	6.78	15.22	ns
	MW-TW	12.11	14.30	**
Sheffield roughness	JW-MW	-20.11	26.79	*
	JW-TW	-30.78	32.05	**
	MW-TW	-10.67	36.72	ns
Air resistance, s/100 ml	JW-MW	-2.67	15.76	ns
	JW-TW	3.00	13.50	ns
	MW-TW	5.67	9.23	ns
Tensile index, N•m/g	JW-MW	-2.56	2.07	***
	JW-TW	-0.78	2.82	ns
	MW-TW	1.78	2.22	**
Stretch, %	JW-MW	0.08	0.13	*
	JW-TW	0.26	0.13	****
	MW-TW	0.18	0.11	***
Zero span breaking length, km	JW-MW	-0.46	0.41	**
	JW-TW	0.68	0.42	***
	MW-TW	1.14	0.65	****
Burst index, kPa•m^2/g	JW-MW	-0.26	0.15	****
	JW-TW	0.02	0.17	ns
	MW-TW	0.28	0.16	****
Tear index, mN•m^2/g	JW-MW	-1.14	0.47	****
	JW-TW	0.87	0.47	****
	MW-TW	2.01	0.25	****
Brightness, %	JW-MW	-4.51	3.44	***
	JW-TW	-4.80	3.33	***
	MW-TW	-0.29	1.61	ns
Printing opacity, %	JW-MW	1.03	0.96	**
	JW-TW	1.18	0.49	****
	MW-TW	0.15	0.49	ns
Scattering coefficient, cm^2/g	JW-MW	60.00	27.88	****
	JW-TW	54.67	26.94	****
	MW-TW	-5.33	17.11	ns

1. ****, significant at 0.1% level
***, significant at 1% level
**, significant at 5% level
*, significant at 10% level
ns, not significant

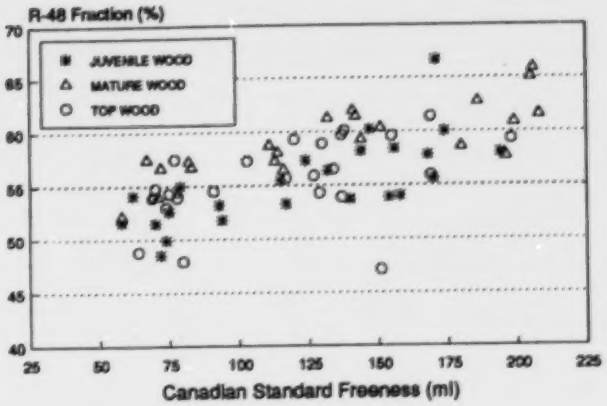


Fig. 12-3 R-48 fraction versus Canadian standard freeness

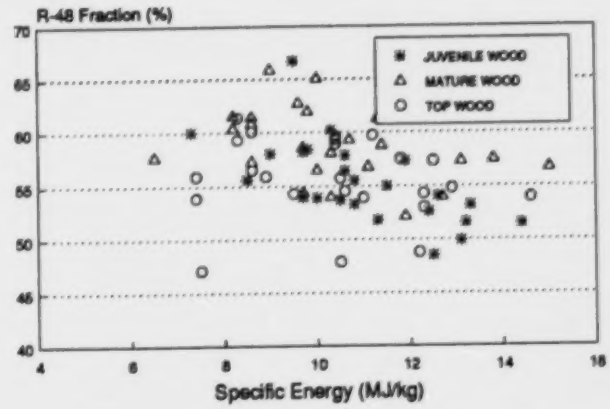


Fig. 12-4 R-48 fraction versus specific energy consumed

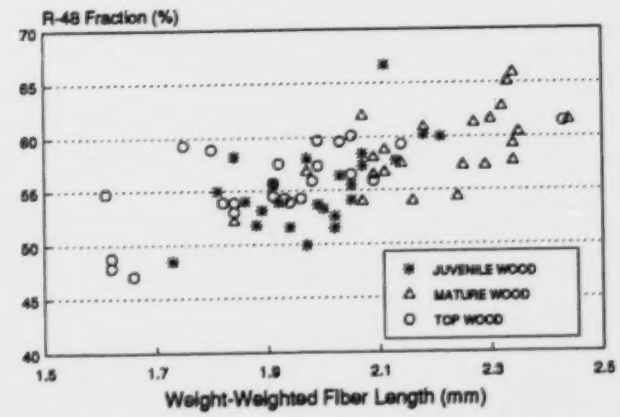


Fig. 12-5 R-48 fraction versus weight-weighted fiber length

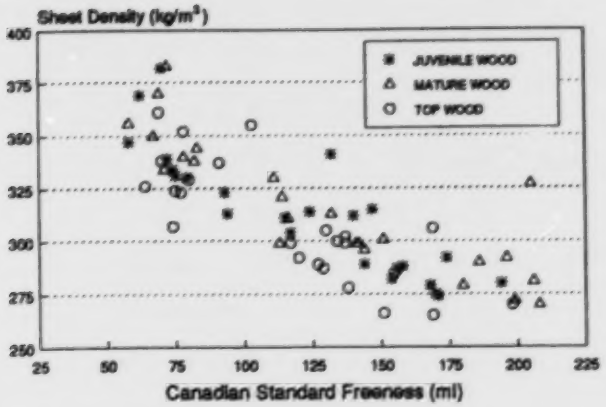


Fig. 12-6 Sheet density versus Canadian standard freeness

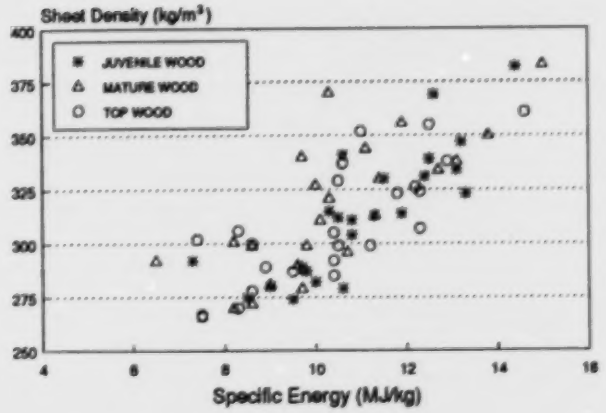


Fig. 12-7 Sheet density versus specific energy consumed

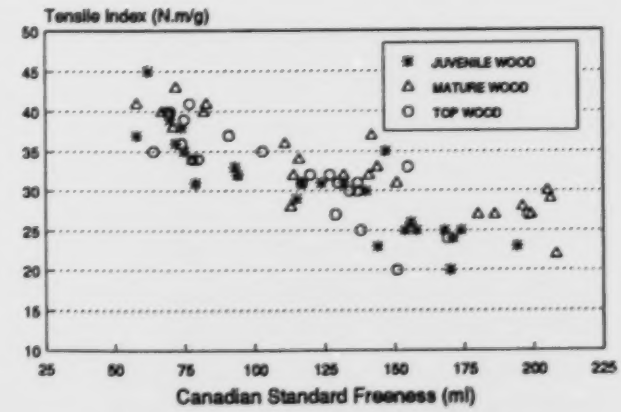


Fig. 12-8 Tensile index versus Canadian standard freeness

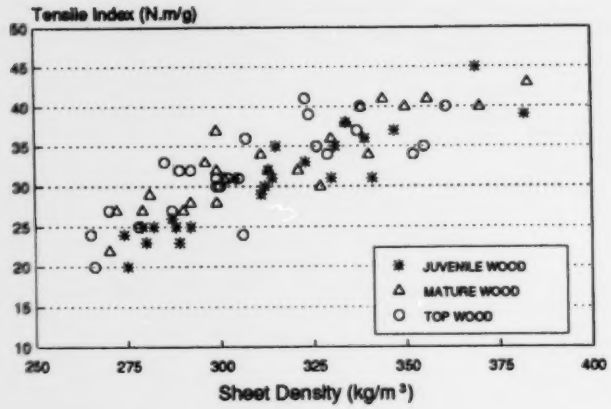


Fig. 12-9 Tensile index versus sheet density

Table 12-8. Paired Statistical Analysis of Refiner Mechanical Pulp Properties at a Sheet Density of 320 Kilograms per Cubic Meter (kg/m^3)

Pulp Property	Test Pair	Mean Difference	Standard Deviation	Level of Significance[1]
Csf, ml	JW-MW	-6.44	21.72	ns
	JW-TW	14.00	25.79	ns
	MW-TW	20.44	22.63	**
Tensile index, N•m/g	JW-MW	-1.89	1.83	**
	JW-TW	-2.44	2.01	***
	MW-TW	-0.55	2.96	ns
Burst index, kPa•m^2/g	JW-MW	-0.19	0.11	****
	JW-TW	-0.04	0.14	ns
	MW-TW	0.15	0.19	*
Tear index, mN•m^2/g	JW-MW	-1.16	0.49	****
	JW-TW	0.98	0.53	****
	MW-TW	2.14	0.28	****
Printing opacity, %	JW-MW	1.32	0.85	***
	JW-TW	1.06	0.43	****
	MW-TW	-0.26	0.56	ns
Scattering coefficient, cm^2/g	JW-MW	66.78	23.60	****
	JW-TW	46.00	20.89	****
	MW-TW	-20.78	17.69	***

1. ****, significant at 0.1% level
***, significant at 1% level
**, significant at 5% level
*, significant at 10% level
ns, not significant

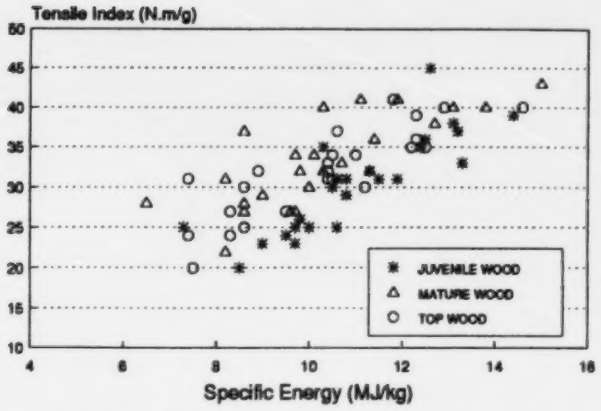


Fig. 12-10 Tensile index versus specific energy consumed

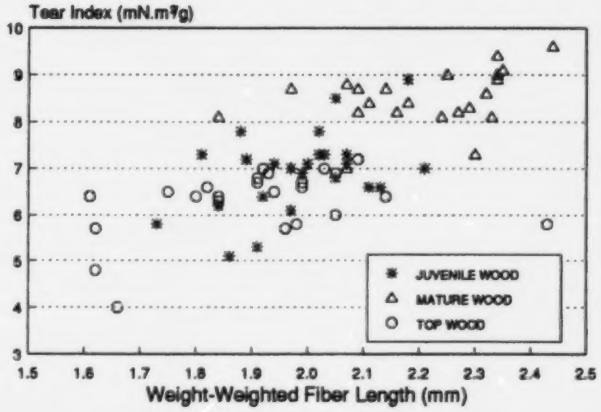


Fig. 12-11 Tear index versus weight-weighted fiber length

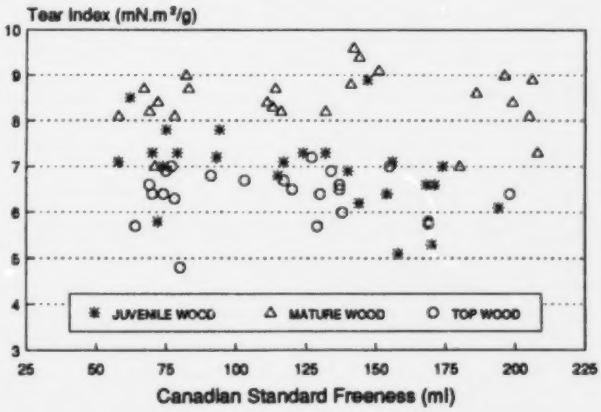


Fig. 12-12 Tear index versus Canadian standard freeness

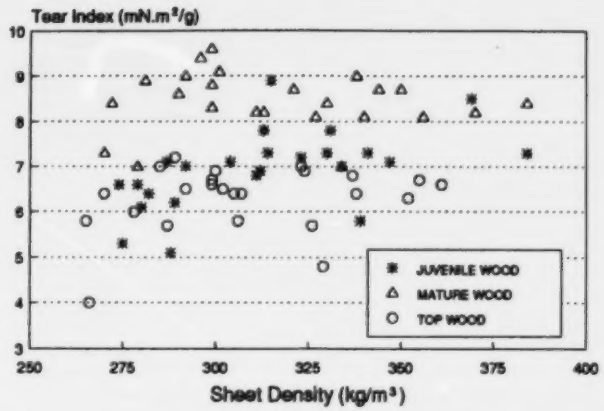


Fig. 12-13 Tear index versus sheet density

Table 12-9. Paired Statistical Analysis of Refiner Mechanical Pulp Properties at a Specific Energy of 10.5 Megajoules per Kilogram (MJ/kg)

Pulp Property	Test Pair	Mean Difference	Standard Deviation	Level of Significance[1]
Csf, ml	JW-MW	17.89	35.64	ns
	JW-TW	19.11	22.70	**
	MW-TW	1.22	38.85	ns
R-48 fraction, %	JW-MW	-1.21	4.08	ns
	JW-TW	0.57	2.84	ns
	MW-TW	1.78	3.69	ns
Sheet density, kg/m^3	JW-MW	-20.22	29.29	*
	JW-TW	-1.89	32.34	ns
	MW-TW	18.33	27.72	*
Tensile index, N•m/g	JW-MW	-5.78	4.60	***
	JW-TW	-3.22	4.89	*
	MW-TW	2.56	4.50	ns
Burst index, kPa•m^2/g	JW-MW	-0.41	0.29	***
	JW-TW	-0.12	0.30	ns
	MW-TW	0.29	0.24	***
Tear index, mN•m^2/g	JW-MW	-1.36	0.75	****
	JW-TW	0.60	0.63	**
	MW-TW	1.96	0.36	****
Printing opacity, %	JW-MW	1.09	1.17	**
	JW-TW	1.21	0.75	***
	MW-TW	0.12	0.57	ns
Scattering coefficient, cm^2/g	JW-MW	35.11	47.23	*
	JW-TW	32.67	27.40	***
	MW-TW	-2.44	42.91	ns

1. ****, significant at 0.1% level
   ***, significant at 1% level
   **, significant at 5% level
   *, significant at 10% level
   ns, not significant

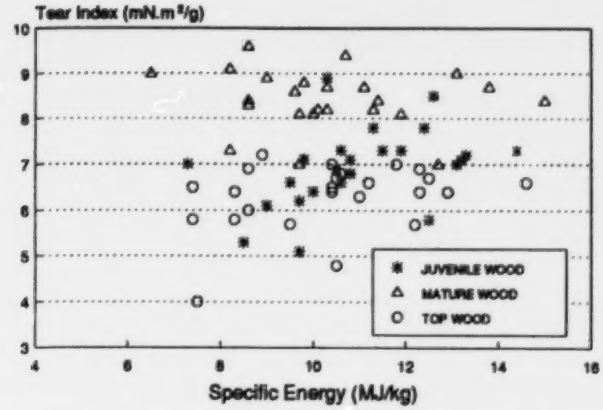


Fig. 12-14 Tear index versus specific energy consumed

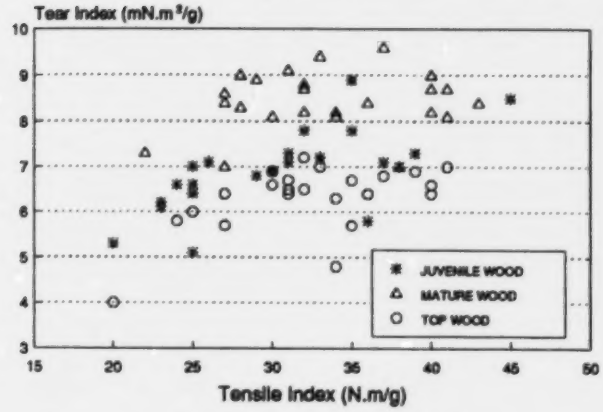


Fig. 12-15 Tear index versus tensile index

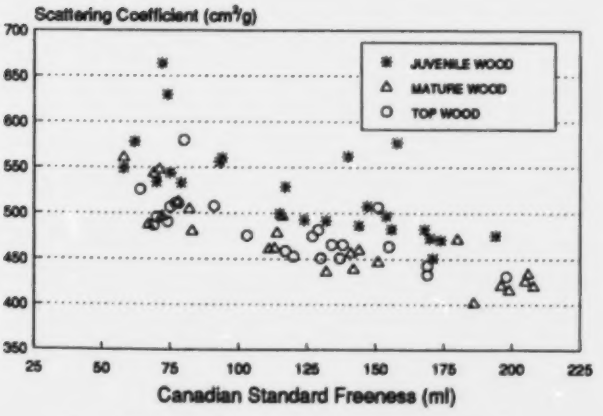


Fig. 12-16 Scattering coefficient versus Canadian standard freeness

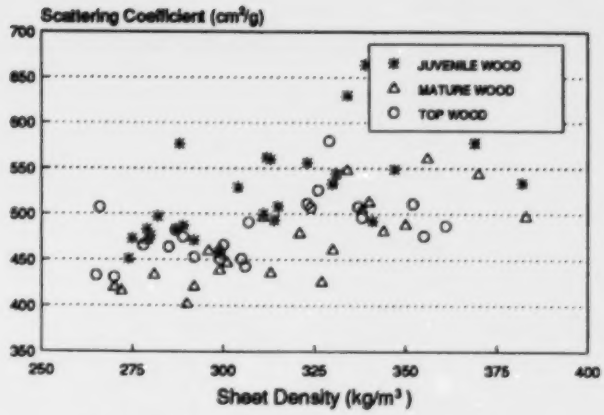


Fig. 12-17 Scattering coefficient versus sheet density

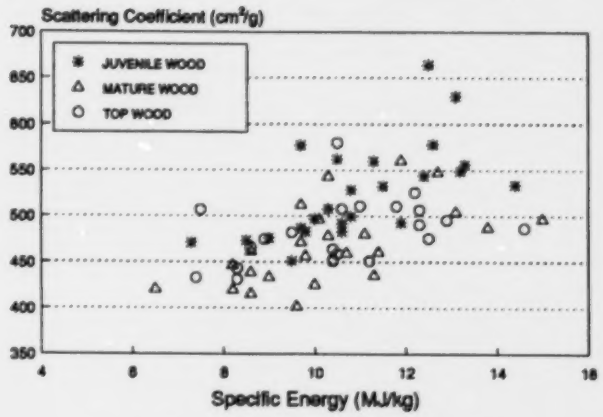


Fig. 12-18 Scattering coefficient versus specific energy consumed

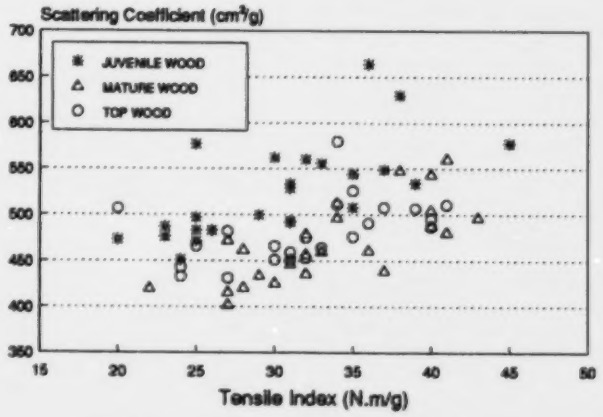


Fig. 12-19 Scattering coefficient versus tensile index

Table 12-10. Summary Statistics from the Data Used to Develop the Prediction Equations for Douglas-Fir Refiner Mechanical Pulps

Variable	Sample Size	Mean	Standard Deviation	Minimum	Maximum
Freeness: 100 milliliters Csf					
Sheet density (SHEET)	27	324.0	14.0	302	356
Tensile index (TENS)	27	34.0	3.2	29	40
Stretch (STRCH)	27	1.93	0.19	1.54	2.32
Burst index (BURST)	27	1.84	0.24	1.3	2.3
Tear index (TEAR)	27	7.3	1.1	4.6	9.1
Scattering coefficient (SCAT)	27	512.0	41.0	462	636
Disk density (DDEN)	27	426.0	57.0	319	558
Chip density (CDEN)	27	420.0	51.0	325	534
Weight-weighted fiber length (FL)	27	1.99	0.17	1.63	2.28
Zero span tensile (ZERO)	27	10.9	0.7	9.4	12.2
R-48 fraction (R48)	27	55.2	2.7	47.7	59.4
Klason lignin, extractive-free wood (KL)	27	28.1	1.5	25.8	31.8
Sheet Density: 320 kilograms per cubic meter					
Tensile index (TENS)	27	34.0	2.8	29	41
Burst index (BURST)	27	1.80	0.19	1.4	2.2
Tear index (TEAR)	27	7.3	1.1	4.7	9.2
Scattering coefficient (SCAT)	27	509.0	44.0	446	632
Weight-weighted fiber length (FL)	27	2.00	0.19	1.63	2.29
Zero span tensile (ZERO)	27	10.8	0.6	9.6	12.1
R-48 fraction (R48)	27	55.6	3.5	47.8	62.9
Specific Energy: 10.5 megajoules per kilogram					
Sheet density (SHEET)	27	314.0	25.0	277	377
Tensile index (TENS)	27	32.0	4.2	25	41
Burst index (BURST)	27	1.67	0.29	1.2	2.3
Tear index (TEAR)	27	7.2	1.1	4.8	9.3
Scattering coefficient (SCAT)	27	498.0	43.0	420	602
Weight-weighted fiber length (FL)	27	2.02	0.16	1.62	2.32
Zero span tensile (ZERO)	27	10.8	0.8	9.5	12.1
R-48 fraction (R48)	27	56.5	3.4	47.9	62.9

Table 12-11. Correlation Coefficients (r) for Data at 100 Milliliters Csf

	Dependent Variables						Independent Variables					
	SHEET	TENS	STRCH	BURST	TEAR	SCAT	DDEN	CDEN	FL	ZERO	R48	KL
SHEET	1.00	0.53	0.10	0.49	0.45	-0.11	-0.02	-0.01	0.48	0.51	0.41	-0.11
TENS	0.53	1.00	-0.06	0.88	0.53	-0.24	-0.10	-0.10	0.45	0.53	0.58	-0.38
STRCH	0.10	-0.06	1.00	0.25	0.55	0.04	0.30	0.37	0.38	0.31	0.20	0.26
BURST	0.49	0.88	0.25	1.00	0.82	-0.33	0.23	0.25	0.69	0.73	0.70	-0.37
TEAR	0.45	0.53	0.55	0.82	1.00	-0.37	0.56	0.61	0.85	0.81	0.68	-0.24
SCAT	-0.11	-0.24	0.04	-0.33	-0.37	1.00	-0.29	-0.30	-0.36	-0.08	-0.76	0.85
DDEN	-0.02	-0.10	0.30	0.23	0.56	-0.29	1.00	0.99	0.44	0.55	0.32	-0.25
CDEN	-0.01	-0.10	0.37	0.25	0.61	-0.30	0.99	1.00	0.46	0.55	0.32	-0.24
FL	0.48	0.45	0.38	0.69	0.85	-0.36	0.44	0.46	1.00	0.69	0.61	-0.20
ZERO	0.51	0.53	0.31	0.73	0.81	-0.08	0.55	0.55	0.69	1.00	0.51	-0.06
R48	0.41	0.58	0.20	0.70	0.68	-0.76	0.32	0.32	0.61	0.51	1.00	-0.67
KL	-0.11	-0.38	0.26	-0.37	-0.24	0.85	-0.25	-0.24	-0.20	-0.06	-0.67	1.00

Table 12-12. Multi-Variable Prediction Equations for Refiner Mechanical Pulp Handsheet Properties at a Freeness of 100 Milliliters Csf

Dependent Variable	Independent Variable Coefficients[1]							
	Intercept	DDEN	CDEN	FL	ZERO	R48	KL	R^2
Sheet density	234.9	-0.124		19.865	12.296	0.097	-1.313	0.456
Tensile index	36.9	-0.040			4.092		-1.066	0.737
Tensile index	38.2		-0.045		4.088		-1.051	0.734
Stretch	-4.07		-0.002	0.165	-0.110	0.053	0.112	0.503
Burst index	0.93	-0.002			0.315		-0.065	0.731
Burst index	0.96		-0.002		0.310		-0.064	0.720
Tear index	-7.4			3.711	0.674			0.821
Scattering coefficient	312.4					-5.134	17.189	0.789

1. valid for $319 \leq DDEN \leq 558$; $325 \leq CDEN \leq 534$; $1.63 \leq FL \leq 2.28$; $9.37 \leq ZERO \leq 12.16$; $47.7 \leq R48 \leq 59.4$; $25.8 \leq KL \leq 31.8$

Table 12-13. Multi-Variable Prediction Equations for Refiner Mechanical Pulp Handsheet Properties at a Sheet Density of 320 Kilograms per Cubic Meter

Dependent Variable	Independent Variable Coefficients[1]							
	Intercept	DDEN	CDEN	FL	ZERO	R48	KL	R^2
Tensile index	77.0	-0.028		-0.142	3.471	-0.445	-1.547	0.454
Burst index	2.09	-0.001		0.117	0.192	-0.012	-0.060	0.405
Tear index	-7.1		0.006	2.190	0.550			0.826
Tear index	-7.0	0.005		2.958	0.589			0.809
Scattering coefficient	403.5					-6.296	16.210	0.857

1. valid for $1.63 \leq FL \leq 2.29$; $9.56 \leq ZERO \leq 12.10$; $47.8 \leq R48 \leq 62.9$

DDEN, CDEN and KL have the ranges shown in Table 12-12

Table 12-14. Three Variable Prediction Equations for Refiner Mechanical Pulp Handsheet Properties at a Specific Energy of 10.5 Megajoules per Kilogram

Dependent Variable	Independent Variable Coefficients[1]							
	Intercept	DDEN	CDEN	FL	ZERO	R48	KL	R^2
Sheet density	474.6				19.342	-3.990	-5.147	0.602
Tensile index	78.1				3.383	-0.624	-1.685	0.744
Burst index	3.25				0.282	-0.031	-0.102	0.820
Tear index	-9.0		0.010	3.757		0.075		0.868
Tear index	-8.4	0.009		3.975		0.069		0.846
Scattering coefficient	579.1				10.658	-9.082	11.273	0.862

1. valid for $1.63 \leq FL \leq 2.32$; $9.52 \leq ZERO \leq 12.14$; $47.9 \leq R48 \leq 62.9$

DDEN, CDEN and KL have the ranges shown in Table 12-12

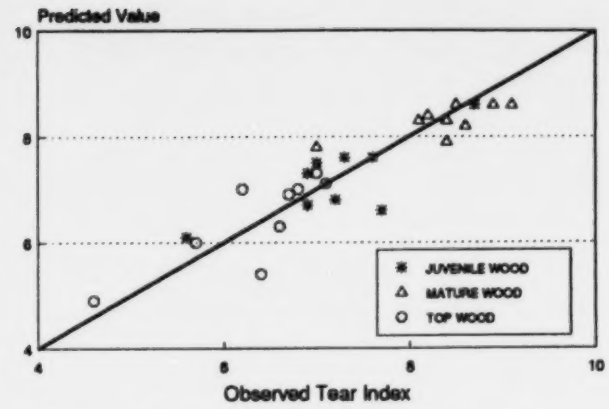


Fig. 12-20 Predicted versus observed tear index values for refiner mechanical pulps at 100 ml Csf

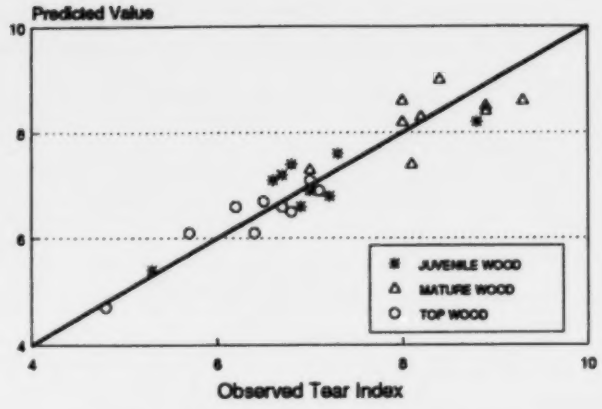


Fig. 12-22 Predicted versus observed tear index values for refiner mechanical pulps at 10.5 MJ/kg specific refining energy

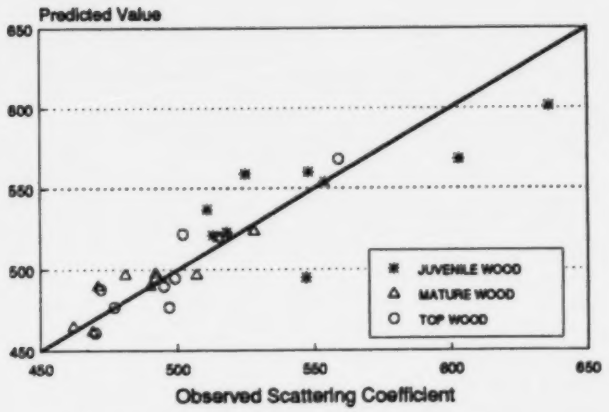


Fig. 12-21 Predicted versus observed scattering coefficient values for refiner mechanical pulps at 100 ml Csf

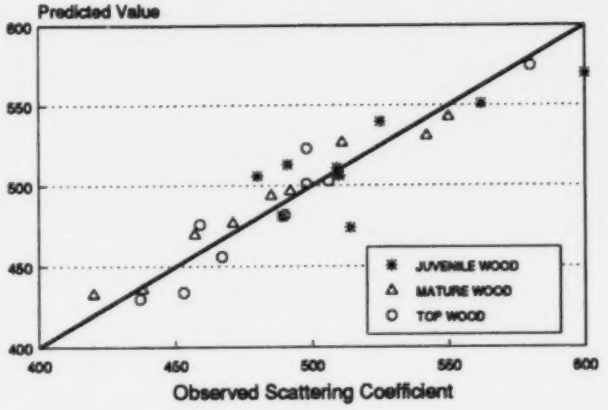


Fig. 12-23 Predicted versus observed scattering coefficient values for refiner mechanical pulps at 10.5 MJ/kg specific refining energy

Table 12-15. Refiner Mechanical Pulp Handsheet Properties at a Freeness of 100 Milliliters Csf Characteristic of Selected Utilization Options for 50-Year Rotation Douglas-Fir

Wood Type[1] or Option	Specific Energy MJ/kg	Sheet Density kg/m^3	Tensile Index N•m/g	Tear Index mN•m^2/g	Scattering Coefficient cm^2/g
Mature wood Option A Option C (separate)	11.0	329	36	8.4	490
Juvenile wood Option C (separate)	11.8	324	33	7.2	550
Option B	11.7	325	33	7.4	540
Option C (mixtures)	11.0 to 11.8	329 to 324	36 to 33	8.4 to 7.2	490 to 550
Top wood Option D	10.9	317	34	6.3	495

1. See Chapter 11 for definitions of options

PART V: Managing the Resource

CHAPTER 13

Silvicultural Treatments and End-Product Value

K.J. Mitchell *Research Branch, B.C. Ministry of Forests*
R.M. Kellogg *Wood Science Department, Forintek Canada Corp.*
K.R. Polsson *Killer Software Engineering*

Introduction

As harvesting in British Columbia shifts from old-growth to second-growth stands, forest planners predict that the volume and value of timber cut will decline to a substantially lower level unless strategies are implemented to elevate the yield and revenue through intensified protection, utilization and silviculture. This study focuses on silvicultural treatment opportunities by developing a management tool that will help planners identify silvicultural practices and environmental factors having the highest impact on standing yield, product recovery and financial return.

It is frequently assumed that the larger volume of wood produced by intensive forest management has proportionately greater value. There is increasing evidence that this is not always true. For example, Forintek Canada Corp. found a decline in strength and stiffness properties relative to established standards (Barrett and Kellogg, 1986) when they investigated the impact of wood properties on the quality of lumber from second-growth stands of coastal Douglas-fir. The report also highlighted the need to relate these findings to silvicultural practices, product value and financial return. That is what the present and foregoing papers in this volume attempt to do. Figure 13-1 traces the flow of information from the preceding chapters to the major sections of the current study (Chapter 13). Chapters 2, 5, 7 and 8 provide the relationships that model wood properties and product quality with the support of Chapters 1 and 3. This information is vital to the systems that grow trees, saw logs, grade lumber and determine end-product value. The studies shown on the right-hand side of Figure 13-1 generate the data which will be needed in the future to model the production of pulp. Likewise, Chapter 9 may contribute to the simulation of treated lumber. The integrated research program depicted in Figure 13-1 culminates in a financial analysis that consolidates treatment response, wood quality, product value, and discounted costs and revenue into a single expression of net value.

The present paper describes the development and initial validation of the system of models, called SYLVER, shown in the lower part of Figure 13-1.

SYLVER

SYLVER simulates the impact of Silviculture on Yield, Lumber Value, and Economic Return. It is a stand-level system designed to rank the merits of alternative treatment opportunities. Social benefits are not considered. No attempt is made to evaluate the effect of cultural practices at the forest level where age-class distribution and other factors may be of overriding importance. The major components that link silvicultural treatments to financial return are illustrated in Figure 13-2. The flow of information is shown in greater detail in Figure 13-3 which serves as a reference for later sections. The current version of SYLVER only applies to second-growth stands of coastal Douglas-fir. Work on interior lodgepole pine, *Pinus contorta* Dougl. var. *latifolia* Engelm., is in the planning stage.

Each element of SYLVER operates independently with information provided by the user or by a preceding element of the system (Figure 13-2). The Tree and Stand Simulator (TASS) grows the stand of trees on a prescribed site and applies silvicultural treatments. The Bucking (BUCK) and Sawmill Simulation (SAWSIM) programs produce logs and lumber from the trees grown by TASS. The grading routine (GRADE) classifies the lumber according to quality. The Financial Analysis System (FAN$Y) determines the discounted net revenue recovered from tending, harvesting and processing the stand. The analyst must interpret the output and integrate it with other management information before making decisions concerning the selection of sites and stands, and the choice and timing of silvicultural treatments.

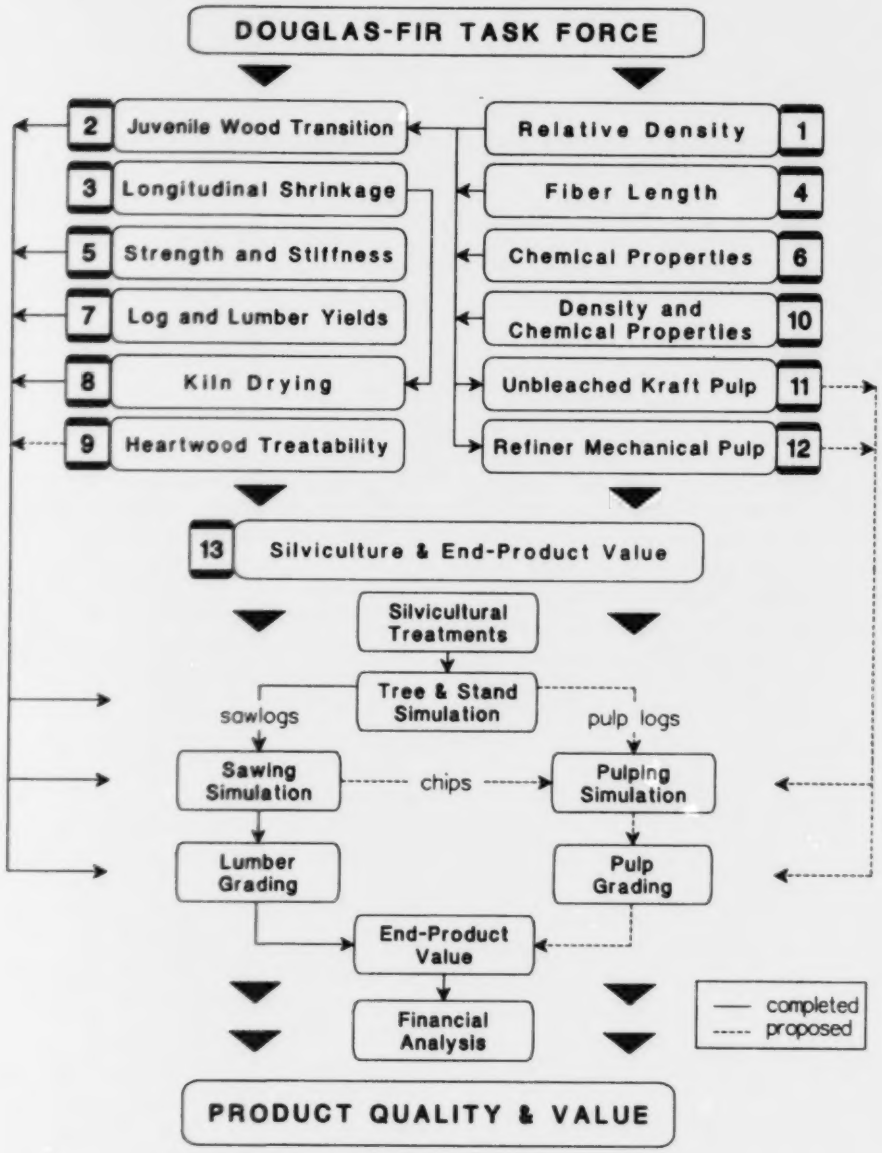


Fig. 13-1 Information flow between Douglas-fir Task Force projects

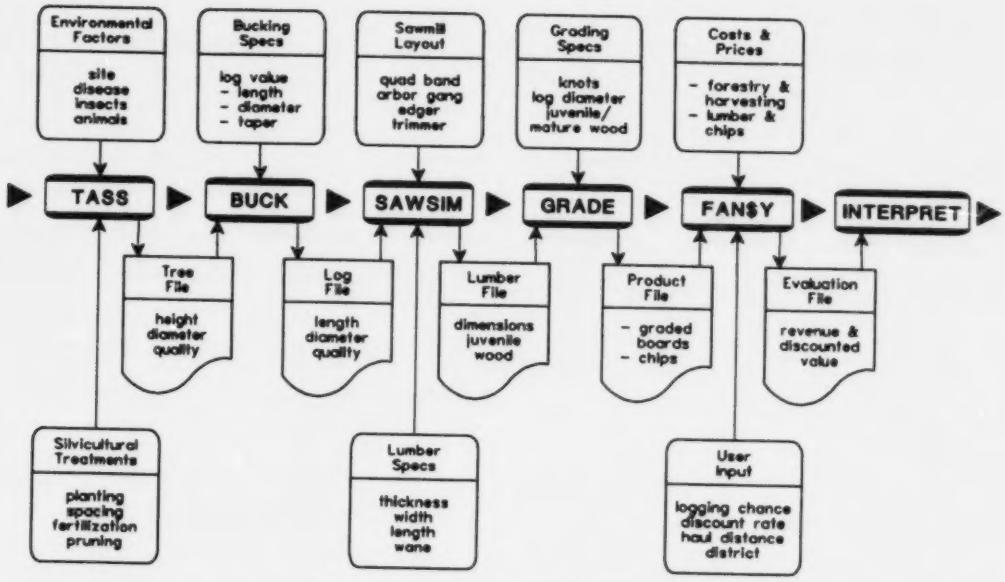


Fig. 13-2 Major components of SYLVER

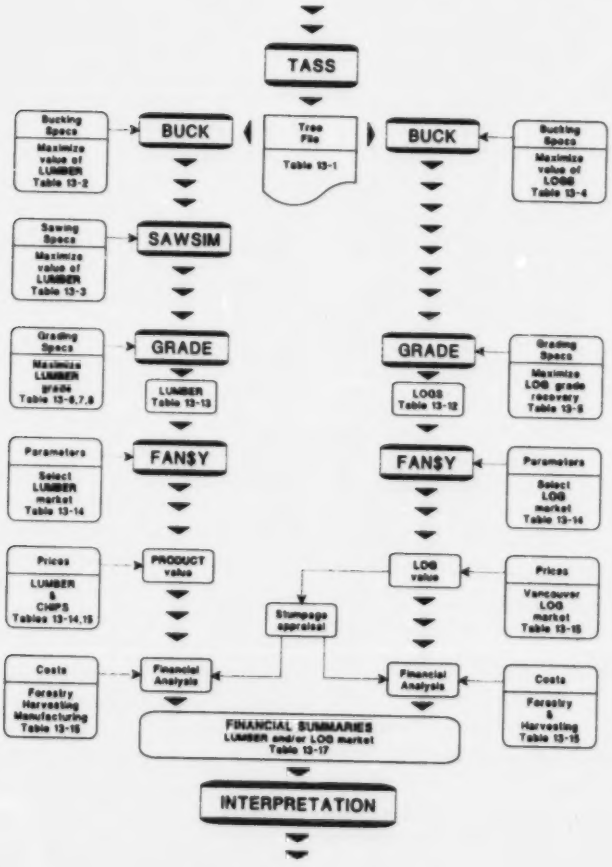


Fig. 13-3 Operation of SYLVER

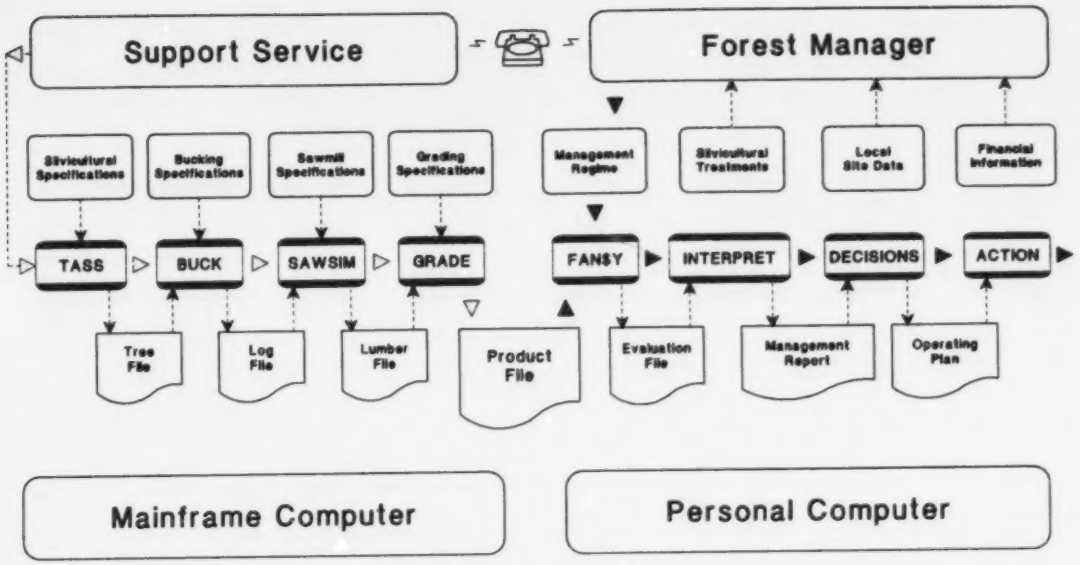


Fig. 13-4 Application of SYLVER

Table 13-1. Tree Data Generated by TASS

Height (m)	Stem Diameter (cm)				Knot Diameter (cm)	
	outside bark	inside bark	inside clear	inside mature	average	maximum
0.00 (base)	57.20	53.26	25.58	23.82	0.00	0.00
0.30 (stump)	54.57	50.81	24.20	21.51	1.09	2.47
0.70	51.39	47.85	21.65	19.26	0.96	2.33
1.30	47.85	44.55	21.49	18.69	1.41	2.82
4.00	43.02	40.06	20.49	16.71	2.55	4.06
6.50 (pruning	40.77	37.96	16.51	13.16	2.38	3.87
6.50 height)	40.77	37.96	37.96	23.22	2.38	3.87
11.50	35.41	32.97	32.97	22.35	2.63	4.14
16.50	29.58	27.54	27.54	21.63	2.89	4.43
21.50	24.03	22.37	22.37	21.63	3.08	4.63
26.50	17.87	16.64	16.64	16.64	2.96	4.50
31.50	10.40	9.68	9.68	9.68	2.25	3.73
36.50	2.86	2.67	2.67	2.67	1.04	2.41
38.47 (top)	0.00	0.00	0.00	0.00	0.00	0.00
	^ bark	^ mature & clear	^ mature w/knots	^ juvenile w/knots		

SYLVER, as depicted in Figures 13-2 and 13-3, is being tested in preparation for its use by forest planners to formulate strategies for guiding the treatment of individual stands. The process is complicated because TASS and SAWSIM must be operated by specialists on mainframe or mini-computers which are capable of completing complex computations in a reasonable time. In contrast, most users only have personal computers and limited time to be trained. The system shown in Figure 13-4 will overcome these problems by dividing responsibilities for operating the system. Support service specialists with access to a mainframe computer will run the modules that generate the product files. The forest manager equipped with a personal computer will perform the financial analyses using FAN$Y, interpret the results, and make decisions based on information from all sources. Initially, both groups will formulate a series of relevant management regimes by specifying silvicultural practices (e.g., planting density, pruning) and treatment levels, and environmental factors (e.g., site quality). Bucking and sawmilling specifications will be standardized. The product file for each regime will be forwarded to the forest manager who will have FAN$Y operating on a personal computer. The user can then define the site productivity and logging chance, enter confidential cost and revenue data for the proposed area and treatment, analyze the information in the product files, and generate the evaluation file. The analyst will be free to compare silvicultural treatments and to test the sensitivity of parameters by altering input data and assumptions. The revenues must be interpreted and compared with other options before decisions can be made and action taken. If a silvicultural regime of local interest is not in the product file, the manager must contact a support service specialist (Figure 13-4).

The following sections describe the characteristics and operation of each component of SYLVER.

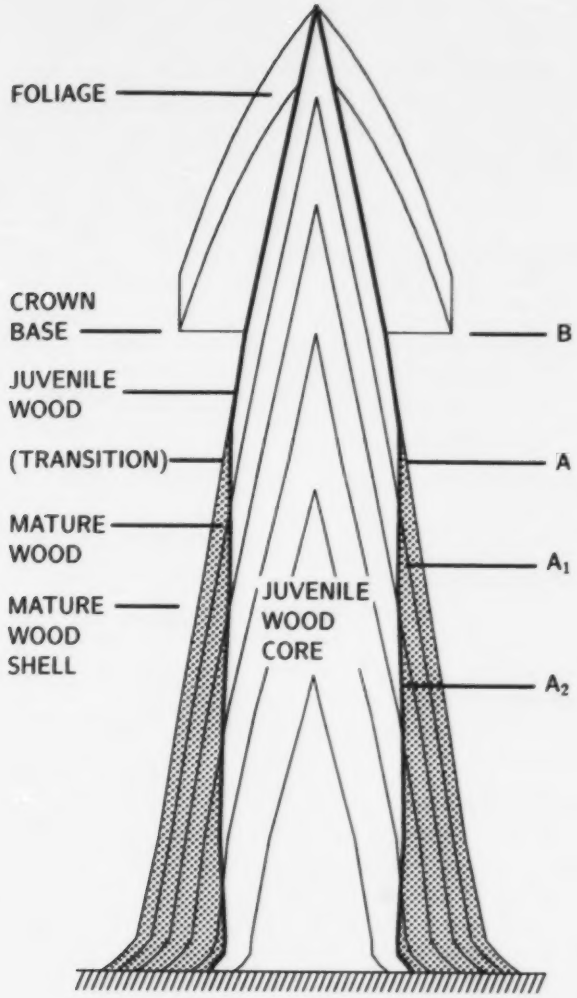


Fig. 13-5 Simulation of juvenile-mature wood transition by TASS

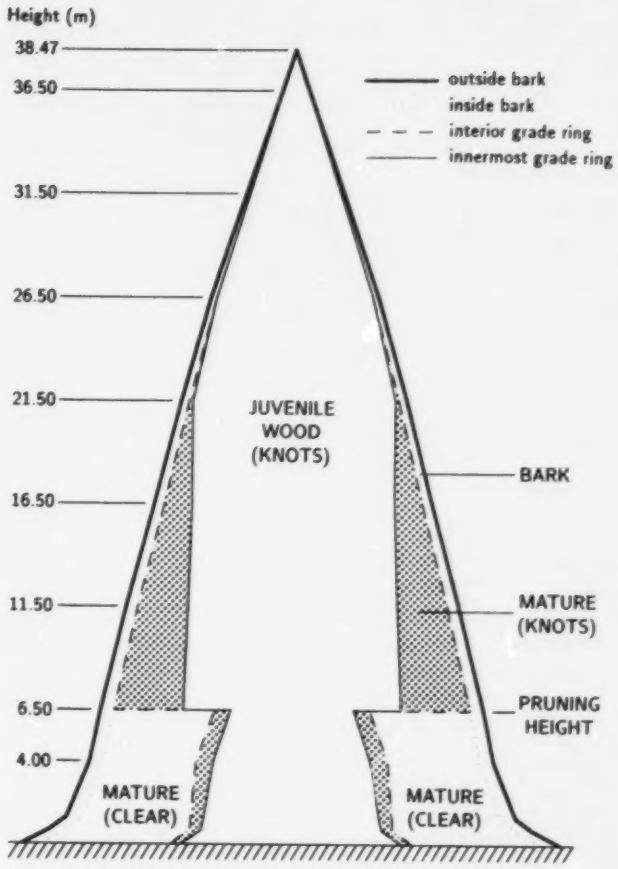


Fig. 13-6 Distribution of wood types in a pruned tree

TASS

The construction of TASS was initiated by the Canadian Forestry Service (Mitchell, 1969) with later support contributed by Yale University (Mitchell, 1975), University of Idaho (Goudie, 1980), British Columbia Ministry of Forests (Mitchell and Cameron, 1985), and other agencies.

Operation

TASS is a biologically oriented model designed to assess the effects of cultural practices and environmental factors on the growth and yield of Douglas-fir (Mitchell, 1975) and other species. It grows trees in a three-dimensional space simulated by a computer. The height-age curve for a particular site drives height increment and branch growth. Genetic variation in height and branch growth ensures that some trees will grow more slowly than others and succumb to competition earlier. Crowns expand and contract asymmetrically in response to internal growth processes, physical restrictions imposed by competing crowns, environmental factors (site quality, disease activity, insect defoliation, animal damage), and cultural practices (espacement, thinning, fertilization, pruning). The crowns annually add a shell of foliage that benefits the tree less and less each year. In the model, the volume increment produced by the foliage is distributed over the bole annually and accumulated to produce tree summaries (Table 13-1) and related stand information.

The model is calibrated to conform to the yield of remeasured plots on coastal British Columbia. Yields reported in the current study are very similar to the Ministry's managed stand yield tables for coastal Douglas-fir (Mitchell and Cameron, 1985). Minor differences are due to recent refinements. Note that these yields will usually exceed those achieved in the operational environment where irregular stocking, pests and other factors contribute to falldown.

Table 13-2. Log Values In Excess Of Chip Value

Taper ("/')	Small End Diameter (in.)	Log Length (ft.)				
		8	12	16	20	24[1]
		(U.S. price/log)[2]				
0.000	4	0.00	0.00	0.00	0.00	0.00
0.000	8	2.09	4.51	7.17	8.84	11.04
0.000	12	6.95	14.78	21.41	26.62	35.90
0.000	16	13.63	29.56	41.60	51.08	71.12
0.000	20	18.09	49.52	68.53	83.84	116.89
0.000	24	21.68	64.93	89.60	109.94	153.80
0.000	28	23.07	76.74	105.11	127.08	179.50
0.000	32	24.46	84.90	115.98	139.83	197.82
0.000	36	25.85	91.98	125.65	151.48	214.31
0.125	4	0.00	0.00	0.87	1.92	3.00
0.125	8	2.09	5.21	8.47	11.39	14.00
0.125	12	6.95	14.82	23.15	28.70	41.14
0.125	16	13.63	29.79	41.96	52.35	74.13
0.125	20	18.09	49.52	69.40	85.69	120.66
0.125	24	21.68	64.93	91.78	112.31	158.57
0.125	28	23.07	76.74	106.78	130.62	184.33
0.125	32	24.46	86.29	118.43	144.32	203.14
0.125	36	25.85	93.80	129.18	156.31	221.80
0.250	4	0.00	0.70	1.95	3.73	5.18
0.250	8	2.09	5.68	9.01	14.61	20.85
0.250	12	6.95	14.95	24.76	33.51	49.03
0.250	16	13.63	29.92	44.72	59.89	86.68
0.250	20	18.09	49.52	71.14	90.15	128.30
0.250	24	21.68	65.91	92.93	116.41	163.14
0.250	28	23.07	78.41	108.65	133.59	188.86
0.250	32	24.46	86.64	119.52	146.80	208.89
0.250	36	25.85	94.11	131.53	159.25	226.44

1. Value of 22-and 24-foot logs was reduced to 10 percent of the amount shown to discourage bucking of these lengths.
2. Value of lumber less revenue received if the entire log was chipped.

TASS was extended to simulate the production of juvenile wood according to the criteria established in Chapter 2. That is, the wood added in a particular year is classified as juvenile wood if it is located above point A in Figure 13-5. Mature wood of relatively high density is produced in the lower portion of the ring. Point A is 3.8 meters below the base of the live crown (B). Point A_1 shows the transition point one year earlier when the base of the crown was lower. The series of transition points in Figure 13-5 traces the lifting of the crown, and defines the inner core of juvenile wood and outer shell of mature wood (shaded). TASS retains the diameter of the juvenile core and outer stem at arbitrary points which usually correspond with stump height (0.3 meter), top of each 5 meter section, and other points (e.g., 0.7 and 1.3 meters) needed to complete the description of bole form. A second grade ring is created by TASS if the tree is pruned. It records the diameter of the branch-free stem following treatment. The inside radius of the clear wood shell is equal to the outside bark radius at the time of pruning, plus the radius of the exposed branch stub. This adjustment removes the branch stubs and healing zone from the shell of clear wood. The transition from juvenile to mature wood along a particular ring is assumed to occur at the upper limit of pruning based on preliminary results reported in Chapter 2.

Average knot diameter (KD) is equal to branch diameter (inside bark) at the surface of the stem. It is calculated annually at the end of each section within the live crown as a function of its distance (L) below the top of the tree. That is:

$$KD = 0.6850L^{0.6122}$$

The diameter at the time of death is retained. KD contributes to the determination of lumber grade. Maximum knot diameter is also needed to grade logs. Its function (not shown) is relatively complex. Equations for estimating branch diameter and knot size were derived by J. Goudie from data collected near Lake Cowichan.

The information passed to the bucking module is illustrated in Table 13-1 and Figure 13-6 for a single tree pruned to 6.5 meters at age 23. Outside bark diameter is needed to calculate the volume of bark, a component of hog fuel scheduled for inclusion in later versions of SYLVER. The double height entry at the upper limit of pruning (6.5 meters in Table 13-1) signals the bucking module to cut the stem at this height and localize the clear wood in the butt log for maximum grade recovery.

Silvicultural Practices

Seven treatments were selected to test the operation of the system on a reasonably productive site (site index = 35). These include planting densities of 300, 400, 500, 600, 750 and 1110 trees per hectare, plus a pruning operation at age 23 in a separate plantation established with 500 trees per hectare. All stems in the later trial were pruned to a height of 6.5 meters leaving an average live crown ratio of at least 0.30 on 97 percent of the trees. The seedlings (2+0) in each regime were planted in a square pattern with a small amount of variation (0.15 meters) permitted about the intended location. Slash burning and early planting were assumed to remove the threat of brush competition. Mortality to age 20 reduced the establishment density to approximately 90 percent of the number planted.

BUCK

BUCK was developed by Halco Software Systems Ltd. to simulate the cutting of trees or long logs.

Operation

Each tree is bucked into the assortment of log lengths that will yield "maximum" value. For example, the pruned portion of the stem, if present, is bucked first to isolate all clear wood in a single butt log to increase grade and value recovery. The bucking of the remainder of the tree is controlled by a log value look-up table prepared by the support service. It includes the value of a matrix of logs which vary in length (8,

Table 13-3. Lumber Prices Used To Select Cutting Pattern

Thick (in.)	Width (in.)	Grade	Length								
			8	10	12	14	16	18	20	22	24
			(U.S. Price/Mbf)[1]								
1[2]	4	clear	650.0	650.0	650.0	650.0	650.0	650.0	650.0	650.0	650.0
1	6	clear	650.0	650.0	650.0	650.0	650.0	650.0	650.0	650.0	650.0
2	4	clear	650.0	650.0	650.0	650.0	650.0	650.0	650.0	650.0	650.0
2	6	clear	650.0	650.0	650.0	650.0	650.0	650.0	650.0	650.0	650.0
2	10	clear	650.0	650.0	650.0	650.0	650.0	650.0	650.0	650.0	650.0
2	4	other	195.5	195.4	200.7	196.3	235.3	225.2	228.9		
2	6	other	194.0	184.7	214.7	199.3	239.3	234.4	238.5	250.0	256.5
2	8	other	186.7	186.5	222.3	205.5	223.4	234.8	246.5	269.7	269.2
2	10	other	188.7	191.7	240.6	256.4	245.0	241.0	238.6	272.0	269.9

1. Average prices for 1976 to 1986 inclusive reported in Random Lengths for 2-inch boards. These prices influence the selection of sawing patterns. Note that the prices applied to lumber for financial evaluation may be different. Average prices for 1981 to 1986 inclusive are provided as default values with FAN$Y, but may be changed by the user.
2. Clear 1-inch boards are assumed to have the same price as 2-inch boards.

Table 13-4. Criteria For Determining The Selling Price Of Logs

Range			Log Grade	Appraisal Log Price ($/m^3)
Small-End Diameter (in.)		Log Length (ft.)		
12 - 36	and	16 - 24	H	62.52
15 - 36	and	12 - 14	I	51.58
4 - 11	and	16 - 24	J	35.51
4 - 14	and	8 - 14	X	25.67
15 - 36	and	8 - 10	X	25.67
4 - 36	and	< 8	Y	14.89

10, 12, ..., 24 feet), small-end diameter (4.00, 4.25, 4.50, 4.75, ..., 8.00, 8.5, 9.0, 9.5, ..., 18.0, 19.0, 20.0, ..., 36.0 inches), and taper (0.000, 0.125, 0.250 inches/foot). An abridged version of the resulting log value table is shown in Table 13-2. Each entry shows the value of lumber cut from the log less a base value, used for analytical purposes, which is equal to the revenue produced by chipping the entire log. The value of the logs represented by each of the 1485 cells in the table has to be determined independently by two different methods because the lumber and log markets do not usually favor the same log lengths. Notice that the financial analysis of lumber and chips in the lower left-hand section of Figure 13-3 uses stumpage appraisal (Crown land only) which is derived from the corresponding value of logs on the right-hand side of the flow chart. Consequently, logs must be bucked and evaluated for both markets if the end products are sold on the coast as lumber and chips. Firstly, each log in the look-up table is cut into boards by SAWSIM (described later) so that log value can be derived from the assortment of boards cut, and a lumber price table derived by the support service in consultation with the users. Recommended prices are shown in the lowermost section of Table 13-3 which applies to boards with knots. This table is based on the average prices reported in Random Lengths Publications (1976-86) for the period 1976 to 1986 inclusive. The prices reported for 22 and 24 foot lengths were subsequently reduced to an arbitrarily low value to discourage the bucking of uncommonly long logs. The unabridged version of Table 13-2 governed the bucking of the simulated trees from all silvicultural treatments as depicted on the left-hand side of Figure 13-3. Secondly, each cell in a companion log value table is assigned a value based on its grade, diameter, length and corresponding selling price on the Vancouver Log Market (Table 13-4). That is, the volume of the log in each cell is calculated and multiplied by the price which corresponds to its diameter and length. Note that a log must satisfy both the diameter and length criteria to qualify for a particular grade and price. The path for bucking and evaluating trees destined for the log market is shown on the right-hand side of Figure 13-3.

The diameter of the stem and the basal diameter of the branches (knots) at each bucking point are interpolated from the information recorded at arbitrary heights by TASS. All data are converted to Imperial units before bucking and sawing.

SAWSIM

SAWSIM is a product of Halco Software Systems Ltd. It was constructed to help the forest products industry evaluate the effects of tree characteristics, bucking practices, mill design, product mixes, and other factors on the productivity and

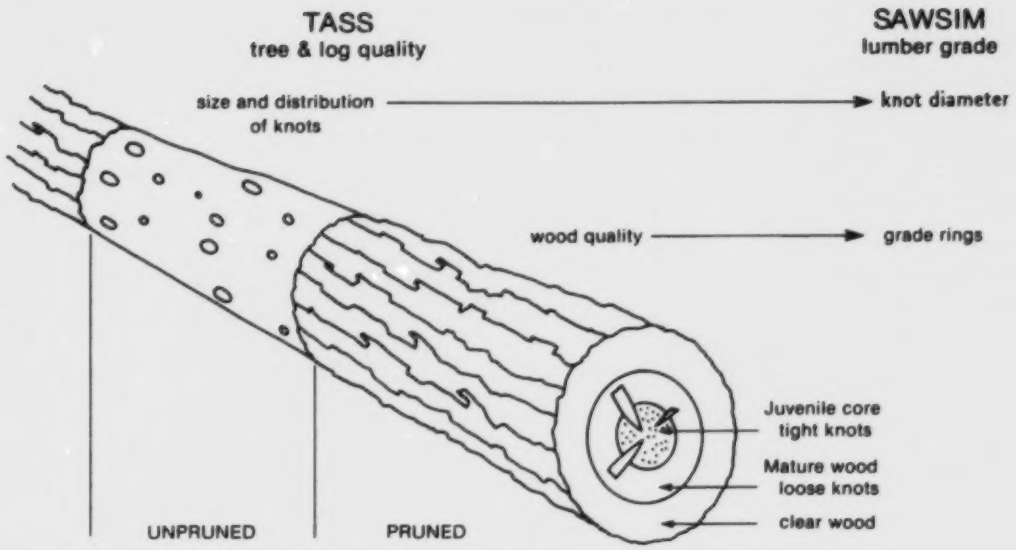


Fig. 13-7 Parameters determining log quality and lumber grade

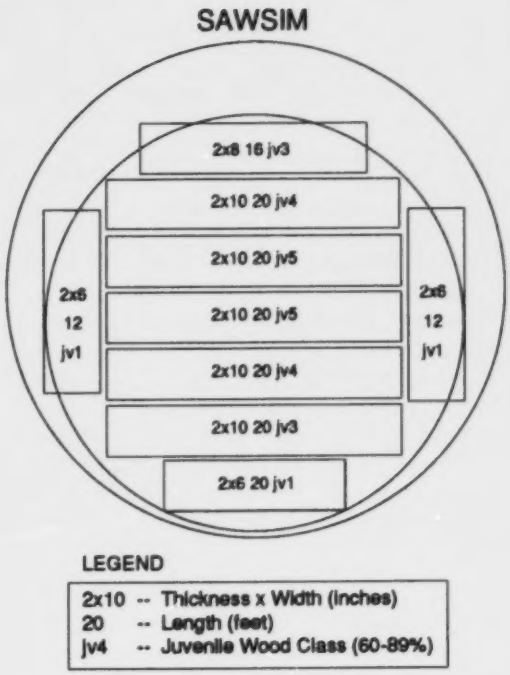


Fig. 13-8 Example of optimum cutting pattern for dimension lumber selected by SAWSIM

profitability of sawmills. It simulates the prescribed layout of the sawmill and determines the cutting pattern that will maximize the value of lumber cut from each log.

The original SAWSIM was employed during the development of the present study. However, computation time was excessive because each silvicultural regime produced about 1000 logs. A streamlined version (SAWSIM-S) was substituted later in preparation for production runs. SAWSIM-S processes straight, uniformly tapered logs using the split-log full-cant or split-log split-cant sawing methods generally used with automatic equipment. Full-log full-cant sawing (i.e., full taper) is not allowed. The diameter of each log was reduced by 0.75 inches (1.9 centimeters) to compensate for sweep, crooks, eccentricity and other factors that reduce lumber recovery. SAWSIM-S operates twice as fast as SAWSIM because the options that compensate for sweep and other features of little importance to this study have been removed. The capacity to handle interior grade rings and knot diameters was incorporated into SAWSIM-S by Halco Software Systems Ltd. as part of this project. SAWSIM-S was also modified to classify each board according to the grade ring from which it originated. The term SAWSIM used in the remainder of this report means SAWSIM-S.

Operation

Figure 13-7 illustrates the log characteristics produced by TASS and BUCK. SAWSIM applies a series of predefined cutting patterns appropriate to the diameter of the log, and selects the one that produces the maximum value of lumber based on the prices shown in Table 13-3. Figure 13-8 shows the cutting pattern selected for a 20 foot Log with end diameters of 13.9 and 16.4 inches.

Table 13-5. Log Grading Criteria And Appraisal Price

Log Grade	End-Product	Minimum Length (m)	Average Small-End DIB (cm)	Maximum Knot Diameter (cm)	Minimum Rings/ 2 cm. DIB outer 1/3[1]	Appraisal Log Price ($/m^3)
A[2]	veneer	5.2	76	--[3]	6	218.37
B[2]	veneer	5.2	60	--[3]	6	145.40
C[2]	veneer	5.2	38	--[3]	5	75.69
D[2]	lumber	5.0	76	--[4]	6	169.77
H	lumber	5.0	30	2[5]	3	62.52
H	lumber	5.0	38	4	3	
H	lumber	5.0	50	5	3	
I	lumber	3.8	38	8	--	51.58
I	lumber	3.8	50	9	--	
I	lumber	5.0	38	10	--	
J	lumber	5.0	10	6	--	35.51
X	lumber	2.6	10	10	--	25.67
X	lumber	2.6	38	13	--	
X	lumber	2.6	76	15	--	
Y	chips	2.6	10	--	--	14.89
reject	hog fuel					--

1. Applies to the outer one-third of the small-end diameter. Not simulated in this version of SYLVER.
2. Only pruned logs can qualify for grades A through D.
3. Must yield at least 35% clear veneer. Optional check not performed
4. Must yield at least 50% clear lumber. Optional check not performed
5. Increased to 3 cm in demonstration runs to increase the volume of H-grade logs in keeping with the results of Chapter 7.

Mill Configuration

For the purpose of the demonstration runs in this report, SAWSIM was configured to conform to a sawmill with the machine centers given below:

Machine	Kerf (inches)
quad band	0.135
double-arbor gang	0.165
edger	0.150

Lumber Specifications

SAWSIM was set up to cut rough lumber of the following nominal dimensions:

thickness	2 inches (1 inch also permitted for clear boards)
width	4, 6, 8, 10, 12 inches
length	10, 12, 14, 16, 18, 20, 22, 24 feet

The maximum allowance for wane was one-third of the thickness or width of the board. The trim was variable.

SAWSIM assigned one of the following quality classes to each board based on the cross-section with the maximum proportion of juvenile wood (i.e., the weakest point):

Quality Class	Juvenile Wood (%)
clear	0
JV1	0-9
JV2	10-39
JV3	40-59
JV4	60-89
JV5	90-100

The application of these quality classes is illustrated in Figure 13-8.

Validation

The actual volume of lumber sawn from 299 Task Force study trees was compared with output from SAWSIM which was instructed to cut trees of the same dimensions. SAWSIM produced an overrun of 5 percent which was reasonably uniform across the range of log diameters. This difference was not removed because it will likely compensate for improvements in sawmill technology expected before today's plantations reach harvest age.

Table 13-6. Lumber Grading Criteria

		classes	
CLEAR (from pruned trees)			
Knot content %	0	1	
Juvenile Wood %	0[1]	1	
Length (ft.)	8, 10, 12, 14, 16, 18, 20, 22, 24	9	
Width (in.)	4, 6, 8, (10, 12)[2]	4	
Thickness (in.)	1, 2	2	
Grade	Clear, (SS, 1, 2, 3, Econ.)[3]	6	
	Combinations (1x1x9x4x2x6)		432
KNOTTY			
Knot Content %	1-100	1	
Juvenile Wood %	0- 9, 10-39, 40-59, 60-89, 90-100	5	
Length (ft.)	8, 10, 12, 14, 16, 18, 20, 22, 24	9	
Width (in.)	4, 6, 8, (10, 12)[2]	4	
Thickness (in.)	2	1	
Grade	Clear[4], SS, 1, 2, 3, Econ.	6	
	Combinations (1x5x9x4x1x6)		1080
	Total Combinations		1512

1. All clear wood is tentatively assumed to be mature wood.
2. Combined because the unit prices are similar.
3. Rundant unless clear are subject to degrade (discussed later).
4. Redundant.

Table 13-7. Degrade Adjustment For Juvenile Wood

Juvenile Wood Content		Original	Revised	Proportion
Code	%	Grade	Grade	Shifted
JV3	40 - 59	1	3	1.00
		2	3	1.00
JV4	60 - 89[1]	1	3	1.00
		2	3	1.00
JV5	90 -100	SS	3	1.00
		1	3	1.00
		2	3	1.00
		3	Econ.	1.00

1. No data recorded - values assumed to be the same as JV3.

GRADE

GRADE characterizes log and lumber quality. The grade and dimensions of each log and piece of lumber for a particular silvicultural treatment and harvest age are stored in the product file (Figures 13-2 and 13-4) along with the quantity of chips, and supporting data. The analysis of this information by FAN$Y is described later.

Products

Logs may be sold on the log market, or converted into lumber and chips by SAWSIM. Each market is simulated independently (Figure 13-3). Logs and lumber are graded according to the rules outlined in later sections. Log summaries include the scaled volume (cubic meters per hectare) by grade, and the number of logs per hectare. Lumber is reported as board-foot volume per hectare by dimension (nominal) and grade, and lumber recovery factor (LRF), where:

LRF = (nominal lumber volume) / (scaled log volume)

Chip recovery is calculated as bone dry units (BDU) per hectare. That is,

BDU = (0.95) (28.08) Vg/2400

where: 28.08 pounds of chips are recovered from each cubic foot of solid green wood (Vg)
2400 pounds is equivalent to 1 BDU
95% of the chips are recovered after screening of undersized chips (fines)

Log Grade

Log grades are needed to calculate the value of logs, and stumpage (Figure 13-3). As mentioned earlier, logs destined for the log market are bucked to maximize their value based on the prices associated with the grades, lengths and diameters in Table 13-4. The volume of these logs by grade and price per cubic meter contributes to the determination of stumpage collected from companies logging Crown land and selling on either the lumber or log market (Figure 13-3).

The grading rules defined in the BCFS Scaling Manual (see Appendix I) were applied to the second-growth logs in this study even though the grading system was developed for logs from old-growth stands. Decay, stain, twist, check, split, pitch pockets, ring shake, sweep, uniformity of color, and burls are not simulated by TASS and were ignored in the determination of grade. The spatial distribution of knots currently being modelled may eventually permit an assessment of their size and distribution over the upper portion of the visible surface of the log as required by scaling procedures.

The criteria for log grade (Table 13-5) incorporate considerable simplification of the official rules for the purpose of this system. Each log is evaluated for inclusion in a particular class starting at the top of the table and progressing downward until its parameters meet the grade criteria. Ring width constraints cannot be applied until TASS is able to store the voluminous data needed to monitor the number of rings per 2 centimeters across the outer one-third of the small-end diameter of each log. However, examination of specialized summaries from TASS indicates that ring width will be acceptable for a prescribed diameter range unless 250 or fewer trees are planted. That is, ring width will not force logs into a lower grade. Only pruned logs qualify for grades A through D. The proportion of clear products, which could be calculated, was ignored because it is not available to the scaler. Initial testing of the grading routine revealed a shortage of H-grade logs, relative to data from Chapter 7, because knot size was too restrictive. For expedience, the grade guideline for one class of H-grade logs was relaxed from 2 to 3 centimeters instead of revising the corresponding function in TASS.

Lumber Grade

SAWSIM produces lumber which is categorized as either clear or knotty. These main groups are further characterized

by proportion of juvenile wood, length, width, thickness and lumber grade (Clear, Select Structural, No. 1, No. 2, No. 3 and Economy) as shown in Table 13-6. The 10 and 12 inch boards were later combined, leaving 4 width classes, because no unit price difference was observed. A total of 1512 classes are available for sorting lumber.

Clear lumber (top of Table 13-6) is only found in pruned trees in second-growth stands because Douglas-fir does not shed dead branches readily. Clear lumber will be free of juvenile wood because the mature wood transition point is shifted upward to the base of the crown created by pruning. This is based on the results of Chapter 2. Otherwise, five classes of juvenile wood would be needed for clear lumber. Any board cut entirely from the clear portion of a pruned tree is categorized as clear lumber.

Each knotty board (Table 13-6) cut by SAWSIM is categorized by juvenile wood content, length, width and thickness, and then apportioned by volume to grade classes as follows:

- *Select* The percentage of select structural lumber volume is calculated from the diameter of the log and surface knots as follows:

$$SS = 46.85 + 0.72\,TD - 17.03\,KD$$

where: SS = volume of select structural lumber (%).
TD = top diameter of the log (centimeter).
KD = average diameter of knots 0.25 centimeters and larger over the length of the log.

The knot diameter and small-end log diameter are based on the knotty core of pruned logs when grading lumber from this portion of the log.

- *Nos. 3 & Economy* Twelve and 8 percent of the volume is apportioned to grades 3 and Economy, respectively.
- *Nos. 1 & 2* The volume remaining after allowing for the above grades (SS, 3, Economy) is divided evenly between grades 1 and 2.

Juvenile Wood Degrade

The grading procedure described in the preceding section assumes that the proportion of juvenile wood does not influence the grade of the board. However, the strength and stiffness study (Chapter 5) shows that the volume of boards in some categories must be shifted to less demanding grades if current standards are to be maintained. The results reported in Chapter 5 have been simplified and implemented as shown in Table 13-7. Note that all boards in each of the eight categories affected are shifted (i.e., degraded) to illustrate the worst scenario. Shifting of juvenile volume among grade categories (Table 13-7) is optional, which permits an evaluation of the impact of juvenile wood content on grade and value described in a later section.

Table 13-8. Degrade Adjustment For Drying

Juvenile Wood Content		Original Grade	Revised Grade	Proportion Shifted
Code	%			
JV3	40 - 59	SS	2	0.03
		1	3	0.02[1]
		2	Econ.	0.01
		3	Econ.	0.01
JV4	60 - 89[2]	SS	2	0.03
		1	3	0.02[1]
		2	Econ.	0.01
		3	Econ.	0.01
JV5	90 -100	SS	3	0.21
		1	3	0.15[1]
		2	Econ.	0.08
		3	Econ.	0.08

1. Interpolated information.
2. No data recorded - values assumed to be the same as JV3.

Table 13-9. Lumber Grade Recovery By Log Grade.

Log Grade	Log Source	Lumber Grade				LRF (fbm/m^3)
		Clear	No. 2+	No. 3	Econ.	
		Lumber Volume (%)				
C	Old growth[1]	26.5	68.8	4.4	0.2	268
	2nd growth[2]	--	85.9	8.7	5.3	301
H	Old growth	34.8	55.8	8.2	1.2	269
	2nd growth	--	84.5	8.8	6.7	301
I	Old growth	9.4	80.8	9.0	0.8	272
	2nd growth	--	82.4	10.4	7.2	292
J	Old growth	3.9	87.2	7.6	1.3	254
	2nd growth	--	83.1	10.0	7.0	256
X	Old growth	7.9	74.0	15.2	2.9	240
	2nd growth	--	76.4	13.7	9.9	194
Y	Old growth	7.4	59.5	27.2	5.9	257
	2nd growth	--	69.9	30.0	--	53
		Grades H, I and J				
Mean	Old growth	16.0	74.6	8.3	1.1	265
	2nd growth	--	83.3	9.7	7.0	283
SYLVER	2nd growth	--	80.0	12.0	8.0	270[3]

1. Middleton and Munro (1985) - grades A, B and D not shown.
2. Log and Lumber Study (Chapter 7).
3. Stand planted with 750 trees/ha and harvested at age 60.

Table 13-10. Components Of Financial Analyses On Public And Private Land.[1]

Land Manager:	Crown	Private			
Land Ownership:	Crown	Crown		Private	
Market:	Timber	Log	Lumber	Log	Lumber
Revenues:	Stumpage	Logs	Limber Chips	Logs	Lumber Chips
Costs:	Management	Management Stumpage Land Rent Harvesting	Management Stumpage Land Rent Harvesting Manufacturing	Management Taxes – Harvesting	Management Taxes – Harvesting Manufacturing
Discount Rate:	4%	(Varies by firm)			

1. Source: B. Howard and D. Coffey, B.C. Ministry of Forests.

Drying Degrade

The lumber drying study (Chapter 8) showed that boards are degraded slightly by kiln drying because of warping. Summaries for 2 x 6 boards were simplified to conform with the structure of FAN$Y. Lumber degrade is applied to all dimensions (Table 13-8) in the same manner as for juvenile wood degrade (Table 13-7).

Validation

Table 13-9 shows that the percentage of lumber volume by grade (Clear, No. 2 & Better, No. 3, Economy) recovered from C, H, I, J, X and Y logs in the study of log and lumber yields (Chapter 7) compares favorably with the distribution of grades reported by Middleton and Munro (1985) for old-growth forests. Mean values for log grades H, I and J, which account for 93 percent of the volume in the Task Force study logs, are summarized in the lower section of Table 13-9. Old growth is slightly lower for grades 2 through Economy. However, this is largely due to the recovery of clear lumber (16.0%) which is not found in the second-growth logs. The distribution of lumber grades used by SYLVER is displayed at the bottom of Table 13-9. It is based on the same data as the preceding line (Chapter 7). Lumber recovery factors shown on the far right of Table 13-9 are generally higher in second-growth stands with an average difference of 18 board feet (7%) for log grades H, I and J.

FAN$Y

FAN$Y provides the manager with a tool for evaluating the impact of selected silvicultural treatments and financial information specified by the user on the value returned by various products. This approach to financial analysis enables the user to identify all treatment options that provide an acceptable return. A manager faced with budget constraints can also rank treatment opportunities by analyzing the information provided by FAN$Y. Table 13-10 outlines the basic components of financial analyses performed by the provincial government and industry when managing forests on Crown and private land. Revenues, costs and discount rate drive the financial analysis. Different revenues and costs concern land managers in the public (Crown) and private sectors. The private land manager derives revenue from the sale of logs, or lumber and chips, whether managing Crown or private land. The costs of private land management include forest management, harvesting and manufacturing. In addition, taxes are payable on private land, while stumpage and land rent are payable on Crown land. Crown land managed by the government yields revenue from stumpage, and incurs forest management costs. The discount rate in FAN$Y can be set by the user. The Ministry of Forests uses 4 percent. Private discount rates will depend on alternative investment opportunities.

FAN$Y was designed and constructed by D. Ormerod and S. Wilson of Sylvametrics Consulting in cooperation with D. Coffey and W. Howard of the British Columbia Ministry of Forests.

Operation

The operation of FAN$Y is depicted in Figure 13-9 with supporting details listed in Table 13-11. The product file is assembled by the GRADE module (Figure 13-4) and distributed to the user with FAN$Y which contains the components illustrated in Figure 13-9. Lumber from the product file is optionally degraded for juvenile wood content or kiln drying, and stored in the regime file from which evaluation reports are derived. The user customizes the process by entering site specific information which replaces default run parameters (e.g., logging chance, haul distance) and economic data (e.g.,

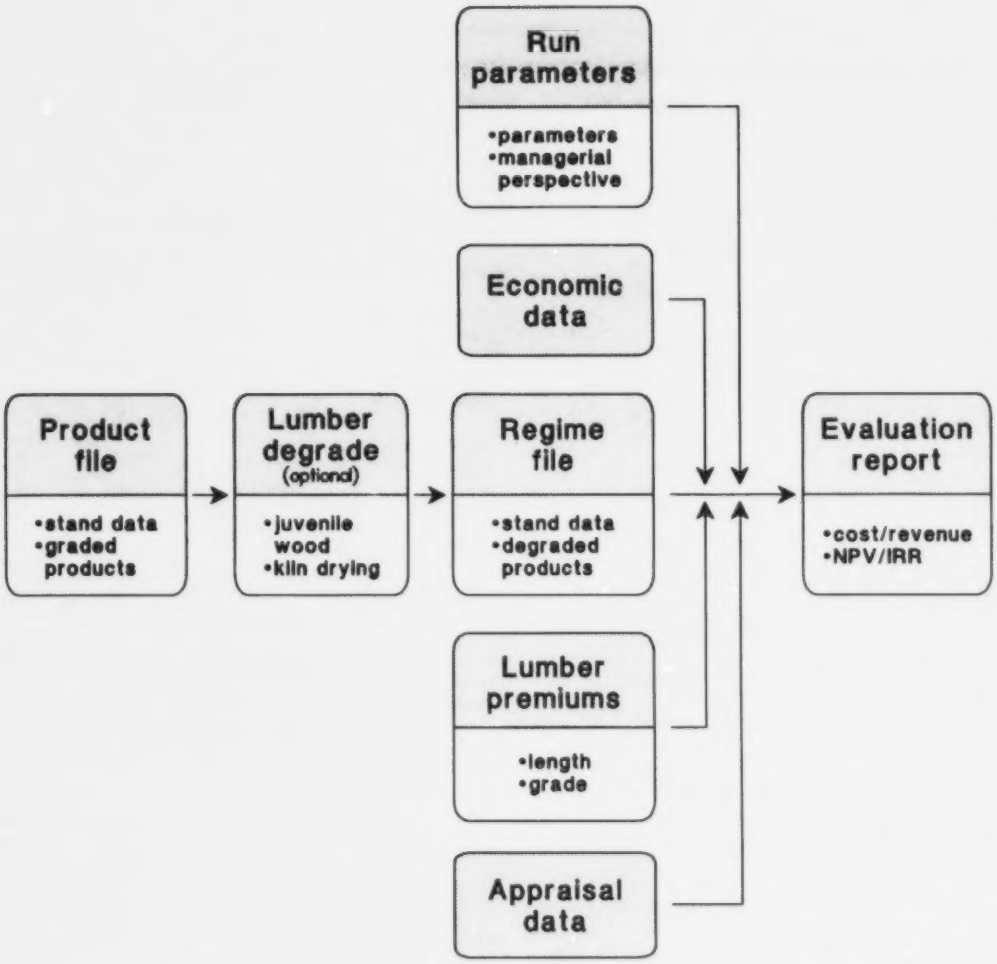


Fig. 13-9 Operation of FAN$Y

unit costs and revenues). Lumber premiums for length and grade, and appraisal data for stumpage calculations may also be altered.

Product File

This external file (Figure 13-9 and Table 13-12) contains site and management information followed by product data for logs, lumber and chips. Silvicultural practices are defined in Table 13-12a, although slash burning is the only one selected in this example. The timing of treatments following stand establishment is also recorded, including the final harvest cut. All harvest ages in the financial analysis are referenced to the time of stand establishment. That is, a 40 year old plantation would contain 42 year old trees, assuming 2+0 stock was used. The board foot volume of knotty lumber is categorized by juvenile wood content, length, width, and grade as illustrated in Table 13-12b. The classes for clear boards, itemized in Table 13-6, are not shown in this example.

Lumber Degrade

This adjustment simulates degrade caused by juvenile wood (Table 13-7), or kiln drying (Table 13-8). The application of FAN$Y is simplified if this procedure is performed before the system is sent to forest managers. That is, the user receives companion sets of regime files for lumber which is adjusted and unadjusted for degrade. FAN$Y is currently configured in this format making it unnecessary to distribute product files or degrade adjustment factors unless requested. The symbols "-" and "^" are appended to the file names (e.g., P50E_60- or P50E_60^) to identify the adjusted and unadjusted versions, respectively. The adjusted regime files contain two independent subsets of data: one with the lumber degraded for juvenile wood content, and another degraded for kiln drying. The unadjusted regime files have two subsets of identical data. Note that the product files and lumber degrade factors can be distributed and implemented by the user because FAN$Y is capable of performing the lumber degrade operation.

Table 13-11. Data Files in FANSY

I.	PRODUCT FILE		filename.PRO
	Species, height, site index, trees/ha		
	Treatments and associated ages; Harvest age		
	Stand yield: stocking, volume, logs/ha, decay		
	Log distribution; Boards/ha		
	Lumber Recovery Factor (LRF)		
	Residual chip recovery: bone dry units		
	Lumber distribution		
II.	LUMBER DEGRADE (adjustment factors)		LUMBRATS.DAT
	Juvenile wood		
	Kiln drying		
III.	REGIME FILE (same items as Product File)		filename.REG
IV.	RUN PARAMETERS		RUNPAR.FIL
	Land Class Index	%	
	Cost Trend	%	
	Price Trend	%	
	Discount Rate: Crown, private	%	
	Distance (harvest site to mill)	km	
	Lumber: Green (G), Dry (D)		
	Exchange Rate ($1.00 US = 1.?? Cdn)		
	Cost Adjustment (relative change/year)		
	Price Adjustment (relative change/year)		
	Selling Zone, District, Silvicultural Type		
V.	ECONOMIC DATA		filename.ECO
	Costs: forestry, harvesting, manufacturing		
	Taxes		
	Prices: logs, lumber, chips		
VI.	LUMBER PREMIUMS		PREMIUMS.DAT
	Green length premiums by width & length		
	Green grade premiums by width & grade		
	Dry length premiums by width & length		
	Dry grade premiums by width & grade		
VII.	APPRAISAL FILE		APPRASAL.DAT
	Rates: base, indicated; Log prices/grade		
	Lumber and chip prices by zone		
	Silvicultural allowances by district & type		
VIII.	EVALUATION REPORT		filename.EVA
	Present net value & internal rate of return		
	Discounted costs and revenues (itemized)		
	Lumber volume		

Table 13-12a. Product File: Stand Information

Species	F: Douglas-fir
Seedling Age	2 years
Site Height	36.7 meters
Site Index	35 meters at 50 years
Years to BH	8 years
Name	P50E_60^
Description	Plant 500/ha: no other treatments
Initial Stocking	500 stems per hectare

Site Preparation

Slash Burn	1
Scarify	0
Chemical	0
Clearing	0

Treatment Ages:		1st	2nd	3rd
Brushing & Weeding:	Man. & Stem Inj	0	0	0
	Man. Fol. Spray	0	0	0
	Aerial Spray	0	0	0
Spacing & Pre-Commertial Thinning		0	0	0
Pruning: 1st	2 - 4 m Lift	0	0[1]	0[1]
2nd	2 - 4 m Lift	0	0[1]	0[1]
Fertilization:	Juvenile	0	0	0
	Late	0	0	0

Stems Treated: (trees per hectare)	1st	2nd	3rd
Spacing & Pre-Commertial Thinning	0	0	0
Pruning: 1st 2 - 4 m Lift	0	0	0
2nd 2 - 4 m Lift	0	0	0

Fertilization Rates: (Kg N/Ha)	1st	2nd	3rd
Juvenile	0	0	0
Late	0	0	0

Harvest Age 60

Stand Yield:

Stocking	438 trees per hectare
Close Utilization	604.5 m^3/ha
Logs/Hectare	1956
Decay	0.0%

Log Distribution Group: m^3/ha

	A	B	C	D	...	H	I	J	...	X	Y
F	0.0	0.0	0.0	0.0	...	112.5	6.5	466.5	...	19.0	0.0

Boards	10771 / ha
Lumber Recovery Factor	282 fbm/m^3
Residual Chip Recovery Factor	
Bone Dry Units (BDU)	90.97 / ha

1. Redundant.

Table 13-12b. Product File: Lumber Volume Distribution (fbm/ha) -- continued

I. CLEAR (no clear lumber in this example)

II. JUVENILE WOOD: 0 - 9%[1]

Species F; Len 8

	C1	C2	SS	1	2	3	4[2]
4	0	0	307	129	129	85	56
6	0	0	159	66	66	44	29
8	0	0	82	30	30	21	14
10	0	0	0	0	0	0	0

Species F; Len 10

	C1	C2	SS	1	2	3	4
4	0	0	305	112	112	79	53
6	0	0	372	145	145	99	66
8	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0

Species F; Len 12

	C1	C2	SS	1	2	3	4
4	0	0	95	32	32	24	16
6	0	0	89	35	35	24	16
8	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0

Species F; Len 14

	C1	C2	SS	1	2	3	4
4	0	0	690	273	273	185	124
6	0	0	342	130	130	90	60
8	0	0	224	73	73	56	37
10	0	0	95	30	30	23	15

Species F; Len 16

	C1	C2	SS	1	2	3	4
4	0	0	319	123	123	85	56
6	0	0	110	51	51	32	21
8	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0

Species F; Len 18

	C1	C2	SS	1	2	3	4
4	0	0	169	74	74	48	32
6	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0

Species F; Len 20[1]

	C1	C2	SS	1	2	3	4
4	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0

Species F; Len 22[3]

	C1	C2	SS	1	2	3	4
4	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0

Species F; Len 24[3]

	C1	C2	SS	1	2	3	4
4	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0

III. JUVENILE WOOD: 10 - 39% (same classes as above)

IV. JUVENILE WOOD: 40 - 59% (same classes as above)

V. JUVENILE WOOD: 60 - 89% (same classes as above)

VI. JUVENILE WOOD: 90 -100% (same classes as above)

1. Lumber with 0 to 9 percent juvenile wood usually originates from large butt logs which are most likely to be bucked into 14 foot lengths to elevate the volume of 2 x 10s and maximize lumber value (see Table 13-3). Consequently, no 20 foot logs were cut from the lower stem in this example.
2. Economy.
3. Log lengths in excess of 20 feet were not requested in this example.

STAND INFORMATION
(same as Product File shown in Table 13-12a)

Lumber Distribution: ftbm/ha

Species F; Len 8

		C1	C2	SS	1	2	3	4[1]
4	G[2]	0	0	937	855	855	397	265
	D[3]	0	0	937	855	855	397	265
6	G	0	0	734	613	613	295	196
	D	0	0	734	613	613	295	196
8	G	0	0	480	253	253	148	99
	D	0	0	480	253	253	148	99
10	G	0	0	106	35	35	26	18
	D	0	0	106	35	35	26	18

Species F; Len 10

C1	C2	SS	1	2	3	4
0	0	1153	1055	1055	489	326
0	0	1153	1055	1055	489	326
0	0	833	627	627	313	208
0	0	833	627	627	313	208
0	0	394	155	155	106	71
0	0	394	155	155	106	71
0	0	82	42	42	25	17
0	0	82	42	42	25	17

Species F; Len 12

C1	C2	SS	1	2	3	4
0	0	852	487	487	274	184
0	0	852	487	487	274	184
0	0	1028	1134	1134	496	330
0	0	1028	1134	1134	496	330
0	0	345	225	225	119	79
0	0	345	225	225	119	79
0	0	858	432	432	258	172
0	0	858	432	432	258	172

Species F; Len 14

		C1	C2	SS	1	2	3	4
4	G	0	0	1864	1199	1199	639	426
	D	0	0	1864	1199	1199	639	426
6	G	0	0	1281	912	912	466	310
	D	0	0	1281	912	912	466	310
8	G	0	0	250	91	91	65	43
	D	0	0	250	91	91	65	43
10	G	0	0	16507	7882	7882	4841	3227
	D	0	0	16507	7882	7882	4841	3227

Species F; Len 16

C1	C2	SS	1	2	3	4
0	0	4580	4699	4699	2096	1398
0	0	4580	4699	4699	2096	1398
0	0	3112	3631	3631	1557	1037
0	0	3112	3631	3631	1557	1037
0	0	738	796	796	350	233
0	0	738	796	796	350	233
0	0	8294	4633	4633	2634	1756
0	0	8294	4633	4633	2634	1756

Species F; Len 18

C1	C2	SS	1	2	3	4
0	0	886	748	748	358	239
0	0	886	748	748	358	239
0	0	94	102	102	45	30
0	0	94	102	102	45	30
0	0	727	669	669	310	206
0	0	727	669	669	310	206
0	0	0	0	0	0	0
0	0	0	0	0	0	0

Species F; Len 20

		C1	C2	SS	1	2	3	4
4	G	0	0	1327	1719	1719	7174	477
	D	0	0	1327	1719	1719	7174	477
6	G	0	0	1928	1915	1915	864	576
	D	0	0	1928	1915	1915	864	576
8	G	0	0	4555	4120	4120	1919	1280
	D	0	0	4555	4120	4120	1919	1280
10	G	0	0	2064	1174	1174	662	441
	D	0	0	2064	1174	1174	662	441

Species F; Len 22[4]

C1	C2	SS	1	2	3	4
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0

Species F; Len 24[4]

C1	C2	SS	1	2	3	4
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0

1. Economy.
2. Green lumber which has not been degraded for juvenile wood content in this example.
3. Dry lumber which has not been degraded for kiln drying in this example.
4. Log lengths in excess of 20 feet were not requested in this example.

Table 13-14. Run Parameters

VARIABLES	EXAMPLE	DEMO RUNS
Land Class Index	10	10
Cost Trend: future change/year	- 1.0 (-1.0 %)	0
Price Trend: future change/year	0.5 (+0.5 %)	0
Discount Rate: Crown	4%	4
Private	5%	4
Distance: harvest site to mill	30 km	30
Lumber: Green (G) vs. Dry (D)	G	G
Exchange Rate: $1.00 US =	1.25 Cdn	1.25
Cost Adjustment (since collection date)	0.950 (-5 %)	0
Price Adjustment (since collection date)	1.100 (+10 %)	0
Selling Zone	1 (coast)	1
District	11 (Chilliwack)	11
Silvicultural Type	1 (coast)	1
SITE INDEX		
Site Indices (maximum of 6)	20, 25, ... 45	35
MANAGERIAL PERSPECTIVE		

	Land manager		Land ownership		Market		Code
1.	Crown (C)	----	Crown (C)	---->	Timber		CC
2.	Private (P)	----	Crown (C)	---->	Log	(G)	PCG
3.				---->	Lumber	(L)	PCL
4.	Private (P)	----	Private (P)	---->	Log	(G)	PPG
5.				---->	Lumber	(L)	PPL

Regime File

The regime file (Figure 13-9 and Table 13-13) is the same as the product file (Table 13-12) except that the juvenile wood categories are combined, and the lumber volumes may have been shifted from one grade to another to imitate the impact of degrade specified in Tables 13-7 and 13-8. Note that the grade distributions of green (G) and dry (D) lumber are identical in Table 13-13 because they have not been degraded for juvenile wood content or kiln drying, respectively, in this example. These files are the basis of the financial analyses.

Run Parameters

Information provided to FAN$Y via this channel (Figure 13-9) is illustrated in Table 13-14 and described below:

Land Class Index

The Land Class Index (LCI) quantifies the "degree of operating difficulty" anticipated when managing and harvesting a particular site. It varies from 0 to 100 with values of 0 to 25 covering the range of conditions encountered in second-growth forests managed intensively in recent years. Values of 5, 10, and 25 are recommended for low-, average-, and high-cost situations, respectively. LCI is based on most of the components of the Logging Productivity Index described in the appraisal manuals of the Ministry of Forests (October 1983 and January 1985) together with an Isolation Rating Table, constructed specifically for FAN$Y. The following costs are affected by LCI:

Forestry Costs:
- Survey and prescription
- Site preparation
- Planting
- Brushing and weeding
- Spacing
- Pruning
- Fertilization

Harvesting Costs:
- Infrastructure development
- Operation, camp and crew transportation overhead
- Central administration overhead
- Tree to truck operation
- Hauling

The relationship of these variables is illustrated and discussed later under "Economic Data".

Cost and Price Trends

These trends reflect the user's prognosis of future changes in real production costs and selling prices. Historically (1920 - 1980), lumber and stumpage prices have increased 2.0 and 6.5 percent per annum, respectively, followed by a sharp decline in the early 1980s (Hay-Roe, 1988). Forintek economist Gilles Brunette reviewed data from various sources to help users formulate reasonable cost and price projections (personal communication). His cautious prognosis indicates that the price of Douglas-fir lumber will increase, in real terms, by 0.5 percent per year in the 1990s, and then decrease by 1.0 percent for the next 50 years. Costs will decrease by 1 to 2 percent per year in the same period.

Future cost and price trends are very uncertain and are left to the discretion of the user. They must be selected with care because they have a considerable impact on the present net value of managed forests, as will be shown later. No cost or price trends are incorporated into the demonstration runs presented at the end of this report.

Discount Rate

Costs and revenues incurred at various ages in the life of a stand are not comparable unless adjusted by means of a discount rate. For example, a revenue of $100 expected 40 years hence is worth more to the owner than $100 realized in 80 years. Similarly, expenditures in the future are more desirable than current costs. Planting and thinning may each cost $500 per hectare at ages 0 and 30, respectively. The manager must spend $500 now to plant but could cover future thinning costs by investing $154 today at 4 percent for 30 years. That is, $500 discounted at 4 percent for 30 years returns:

$$\$500 / [1 + (4 / 100)]^{30} = \$154$$

The discounted value of costs and revenues is very sensitive to the discount rate, especially for long rotations. Higher discount rates favor practices with early revenues and late

expenditures. The Ministry of Forests uses a real rate of 4 percent. Private companies would choose a rate based on alternative investments opportunities.

FAN$Y determines the present value of the future cash flows at the beginning of the year on the assumption that they occur at the mid-point of the year. Surveying, site preparation and planting costs, for example, are not incurred until six months after the evaluation is performed and therefore must be discounted for 0.5 years. That is, planting costs of $400 can be met July 1 by investing $392 January 1 at 4 percent. Annual expenditures (land rent, overhead and protection, taxes) are not affected.

Distance

Distance records the number of kilometers logs must be hauled to the sawmill or log market. The harvesting cost function described later must be altered if logs are transported by water.

Lumber: Green/Dry

The green(G)/dry(D) indicator allows the user to manufacture and sell green or dry lumber. The drying option affects the manufacturing cost, selling price, and net revenue. Green and dry lumber will incorporate the impact of degrade for juvenile wood and kiln drying, respectively, only if the appropriate degraded adjustments (Figure 13-9) are made by the user or incorporated into the regime files distributed with FAN$Y. It is not possible to combine degrade for juvenile wood content and kiln drying.

Exchange Rate

Lumber prices in United States dollars and premiums for length and grade were obtained from Random Lengths (1976-86) and the Western Wood Products Association (WWPA) Monthly F.O.B. Price Summaries (1976-86). The current exchange rate (September 1988) is used to convert the financial summary to Canadian currency in the demonstration trials.

Cost and Price Adjustments

The prices and costs provided with FAN$Y may be out of date for a particular application. The user can enter new information or request that the stored data be inflated or deflated by an appropriate amount. For example, a cost adjustment of 0.950 would decrease all costs in FAN$Y's files by 5 percent. A second entry of 1.100 could increase prices by 10 percent. These run parameters must not be confused with the cost and price trends, described earlier, which escalate or de-escalate expenditures and revenues over time. A price adjustment of 1.150 (15 percent) in combination with a price trend of 0.5 percent would elevate resident lumber prices from $100 to $115, and then escalate them by 0.5 percent per year until harvest age, thus adding another $40 which would bring the final selling price in 60 years to about $155.

Selling Zone, District, Silvicultural Type

The appraisal of timber and determination of stumpage recognize differences in log, lumber and chip prices by species in each of 32 selling zones in British Columbia. Silvicultural allowances compensate for differences in treatment costs in each of 46 districts and 6 silvicultural types. Lumber prices and other data are determined by the Ministry of Forests for appraisal purposes and do not necessarily conform with other information provided in FAN$Y (e.g., lumber prices in Table 13-3). The yield information (regime files) distributed with the current version of FAN$Y applies to coastal Douglas-fir in Selling Zone 1, Silvicultural Type 1, and any one of the following districts:

Code	District
11	Chilliwack
12	Maple Ridge
13	Squamish
14	Sechelt
15	Powell River
16	Duncan
17	Port Alberni
18	Campbell River
19	Port McNeil
1A	Mid-Coast

Site Index

Each product file contains the logs, lumber and chips produced by a particular silvicultural regime, site index and harvest age. For example, Table 13-12a illustrates a stand in which 500 trees were planted per hectare on site 35 and harvested at age 60 when the site trees were 36.7 meters tall. Stands will reach this height at different ages on sites of higher or lower productivity as shown below:

Site Index	Harvest Age	Site Height
45	41	36.7
40	49	36.7
35	60	36.7
30	78	36.7
25	119	36.7

This information can be obtained from site index curves or tables such as those used by TASS to calculate the height of Douglas-fir (Bruce, 1981). There is evidence that each combination of site and harvest age will produce the same yield for a particular site height and silvicultural regime, assuming all other factors are identical. The rationale and methodology are explained by Mitchell and Cameron, 1985. The user of FAN$Y may temporarily override the site index in the product file by entering a new value as a run parameter. The system will calculate the corresponding harvest age. Up

Table 13-15. Economic Data File: Variables And Sample Data[1]

FORESTRY COSTS ($/hectare)	example[2]
Annual Land Rent (accumulated to age 60)	151.12
Surveys/Prescription	7.49
Site Preparation: Slash Burn	184.11
Site Preparation: Scarify	
Site Preparation: Chemical	
Site Preparation: Other	
Planting	432.62
Brush/Weed: Man.+ Stem Inject	
Brush/Weed: Man. Foliar Spray	
Brush/Weed: Aerial Spray	
Spacing & P/C Thinning: 4 m	
Spacing & P/C Thinning: 9 m	
Spacing & P/C Thinning: 15 m	
Pruning: 2 - 3 m Lift	
Pruning: 5 - 7 m Lift	
Fertilization: Juvenile	
Fertilization: Late	
Annual Overhead & Protection (accum. to age 60)	600.00
HARVESTING COSTS ($/m^3)	
Infrastructure Development	2158.92
Operation, Camp & Crew Transportation Overhead	1692.53
Central Administration Overhead	621.93
Tree-to-Truck	10551.83
Water Dump, Boom, Tow & Dewater	---
Hauling	1501.50
Sort and Scale	1473.79

MANUFACTURING COSTS	GREEN	DRY[3]
Number Workers/Shift	55.00	(57.25)
Average Wage	22.50	
Operating Cost/Shift	4500.00	(5570.00)
Admin & Depreciation Cost/Shift	3000.00	(3570.00)
Logs Processed/Shift	2900.00	
Log Processing Proportion	1.00	
Average Pieces/Log	5.00	
Cost/Log	6.00[4]	
Cost/Piece	0.00	

TAXES	
Annual Property Tax	10.00

LOG PRICES (CDN $/m^3) : by species (F) and grade (A-Y)

	A	B	C	D	H	I	J	X	Y
F	154.39	101.57	66.70	114.10	54.68	46.98	32.30	17.63	7.83

LUMBER PRICES ($US/1000 FBM) 4-10" widths GREEN : DRY PREMIUM

	4	6	8	10+	Green/Dry Diff.
F	168.30	162.20	168.20	220.80	30.00

CHIP PRICES ($/BDU): by species (F): used on the coast of B.C.

F
50.00

1. Costs apply to a stand having an LCI of 10 planted with 500 trees/ha. No further treatments are applied before harvesting 604.5 m^3 at age 60.
2. Undiscounted costs calculated using forestry and harvesting cost functions. The corresponding coefficients are normally displayed in this section.
3. Substitute costs if lumber is dried.
4. [[(55 workers x $22.50 x 8hr) + $4500 + $3000]/2900 logs] x 1.00

to six site indices may be entered, thus allowing the user to perform financial evaluations on a range of sites in a single run.

The relationship of site index, harvest age and site height requires clarification. Site index is derived from site height and age at breast-height (Mitchell and Polsson, 1988). Harvest age is the sum of breast-height age and the number of years required by site trees to reach breast height, less the age of planted seedlings. For example, the corresponding entries at the top of Table 13-12a are calculated as follows:

Site height (SH)	=	36.7 m	
Site index (SI)	=	35.0 m	
Age at breast-height	=	54	= f(SH,SI)
Years at breast-height	=	8	= f(SI)
Seedling age	=	2	
Harvest age	=	54 + 8 - 2	= 60

Site index, years to breast height and seedling age may be altered by the user.

Managerial Perspective

The code for managerial perspective identifies the manager (Crown or private) of the land, the owner (Crown or private), and the primary market of the end products (standing timber, logs, lumber) as illustrated in the lower part of Table 13-14. Perspective 1 shows that the Crown sells standing timber from Crown forests. In perspectives 2 and 3, the private sector manages Crown land and may sell logs directly, or manufacture and sell lumber and chips. Perspectives 4 and 5 apply to privately owned forests. The perspective selected in Table 13-14 guides the course of the financial analysis, particularly the determination of costs and revenues (Table 13-10). One or more perspectives may be analyzed simultaneously.

Economic Data

Table 13-15 itemizes the costs (forest management, harvesting, manufacturing and taxes) analyzed by FAN$Y (Figure 13-9) in addition to the price of logs, lumber and chips. The user may customize this information for a particular site.

Forestry Costs

Forestry costs processed by FAN$Y are listed at the top of Table 13-15. The user may enter the costs per hectare for a particular management regime or rely on information calculated by the system using the cost functions, some of which are displayed in Figure 13-10. The forestry costs for some silvicultural treatments (e.g., planting, spacing, pruning, fertilization) are only relevant to a particular financial evaluation if the corresponding product (Table 13-12a) and regime files include the treatment. Irrelevant costs are ignored. FAN$Y calculates all forestry costs as they occur over the rotation, beginning with stand establishment and ending with the harvest.

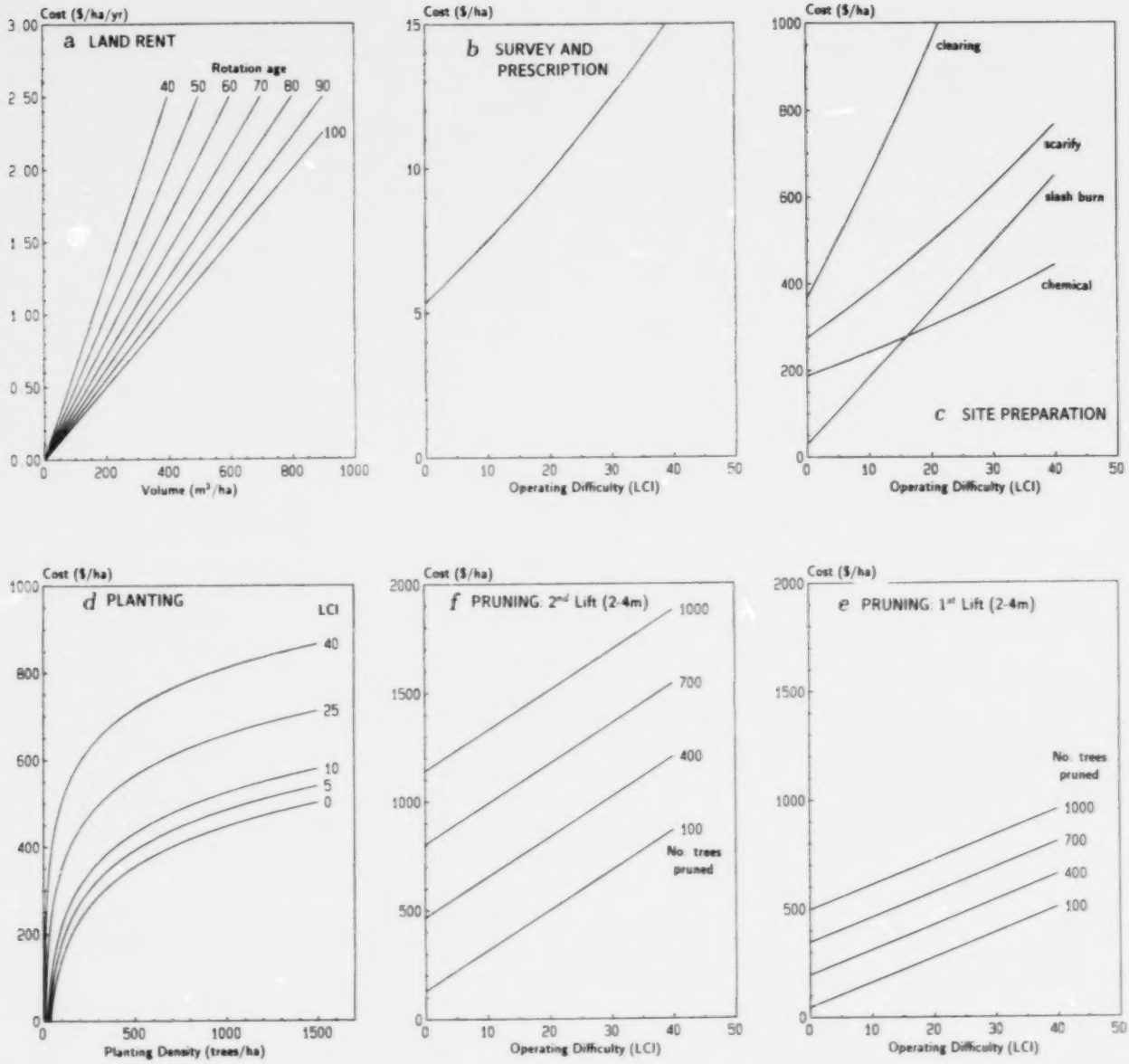


Fig. 13-10 Forestry cost relationships for:
(a) land rent,
(b) survey and prescription,
(c) site preparation,
(d) planting,
(e) pruning - 1st lift,
(f) pruning - 2nd lift,

Forestry cost equations for survey and prescriptions, site preparation, planting, brushing and weeding, spacing and precommercial thinning, pruning, and fertilization are based on survey questionnaires returned by 10 companies and agencies. Respondents provided cost data for "low", "average" and "high" cost situations, and described the associated conditions. Sylvametrics Consulting collected and summarized the confidential data and concluded that these levels of operating difficulty correspond to LCIs of 5, 10 and 25, respectively.

Some forestry costs, such as reforestation, may be viewed as a cost of harvesting rather than a cost of establishing a stand. It can be argued that public opinion and government regulations demand that all Crown forests be reestablished, thus eliminating the optional status of stand establishment. Planting, for example, would then become a harvesting cost incurred at the end of the rotation. Discounting these costs to the present would minimize the impact of establishment expenditures, effectively increasing the net present value. As an alternative, the manager might only consider those silviculture costs in excess of the minimum required by the public or government. This approach would not affect the ranking of espacement opportunities and would thus retain the integrity of the analysis.

Annual Land Rent The amount paid per hectare per year for the use of the land is the annual land rent. The Crown currently charges $1.25 per hectare per year for Timber Licenses, or bases the rent on the productive capacity of the land in terms of its average annual volume growth (i.e., mean annual increment). The default relationship in FAN$Y (Figure 13-10a) derives annual land rent ($ 0.25 per cubic meter per hectare) from mean annual increment if site specific data are not provided by the user. For example, a stand which grows 10 cubic meters per hectare per year would generate an annual land rent of $2.50 at $0.25 per cubic meter. The manager of private land may prefer to exclude the cost of land rent initially and use the net discounted revenue to determine land rent after subtracting an allowance for profit and risk. This perspective is assumed if the annual land rent in the economic file (Table 13-15) is set to zero by the user. The land rent illustrated in Table 13-15 is calculated from mean annual increment (MAI), harvest volume (Table 13-12a), harvest age and annual land rent (rate) as follows:

land rent = MAI x rate x age
= volume/age x rate x age
= volume x rate
= 604.5 m^3 x $0.25
= $151.12

Surveys and Prescription The land is usually surveyed to determine its area and condition (physical and biological). This information contributes to the formulation of a silvicultural prescription and management plan. FAN$Y assumes an initial cost of $5.35 per hectare which increases in relation to the LCI or operating difficulty of the site on which the survey and prescription is undertaken (Figure 13-10b). The example in Table 13-15 shows a cost of $7.49 for LCI 10.

Site Preparation This treatment may utilize slash burning, scarification, chemical sprays, land clearing, or any combination applied in the year of stand establishment. Slash burning of logging debris is the most common method of site preparation on the British Columbia coast. Figure 13-10c shows that slash burning costs about $29 per hectare under ideal conditions, but rises rapidly as the operating difficulty increases from a "low" LCI of 5 ($107 per hectare) through an "average" LCI of 10 ($184 per hectare) to a "high" LCI of 25 ($416 per hectare). This range of LCI applies to second-growth stands which have been treated recently on the coast. Chemical treatment has a higher initial cost ($188 per hectare) but is less sensitive to increases in LCI (Figure 13-10c). Clearing might include stump removal in stands infected with root rot. TASS assumes that the land is reasonably free of slash when it establishes and grows the stand, and automatically informs FAN$Y, via the product and regime files, that slash burning has occurred (Table 13-12a). The user may cancel this treatment and select an alternative regime.

Planting Nursery and planting costs are determined by the number of trees planted and the operating difficulty (LCI) as shown in Figure 13-10d. Planting 500 trees on LCI 10, for example, costs $433. Doubling the establishment density increases the investment to $525. The incremental cost ($0.18/tree) is unreasonably low, and will be revised in future versions of FAN$Y.

Brushing and Weeding Trees may encounter brush competition which is intense enough to impede the height development and survival of the plantation. Since TASS assumes that trees are free growing after establishment, the user must specify the type and frequency of treatments if brushing or weeding is needed to ensure unimpeded growth (Table 13-12a). Cost functions are available for manual brush removal (stem injection, foliar spray) and aerial spray.

Spacing and Precommercial Thinning Juvenile spacing is the primary means of reducing competition in overly dense stands where individual trees are too small to have commercial value. This treatment usually favors trees that are healthy, vigorous, well-spaced and of good form. The growth per hectare can then be concentrated on fewer trees. Consequently, an investment in spacing should reduce harvesting and manufacturing costs and increase product value. This is only relevant if the regime being analyzed includes a spacing. That is, the corresponding stand grown by TASS must have been spaced at one or more ages (maximum of 3) during the simulation. The age and intensity of each treatment will be recorded in the product (Table 13-12a) and regime files. Spacing costs are available for stands which are 4, 9 and 15 meters tall. FAN$Y will apply the function that most closely matches the height of the stand.

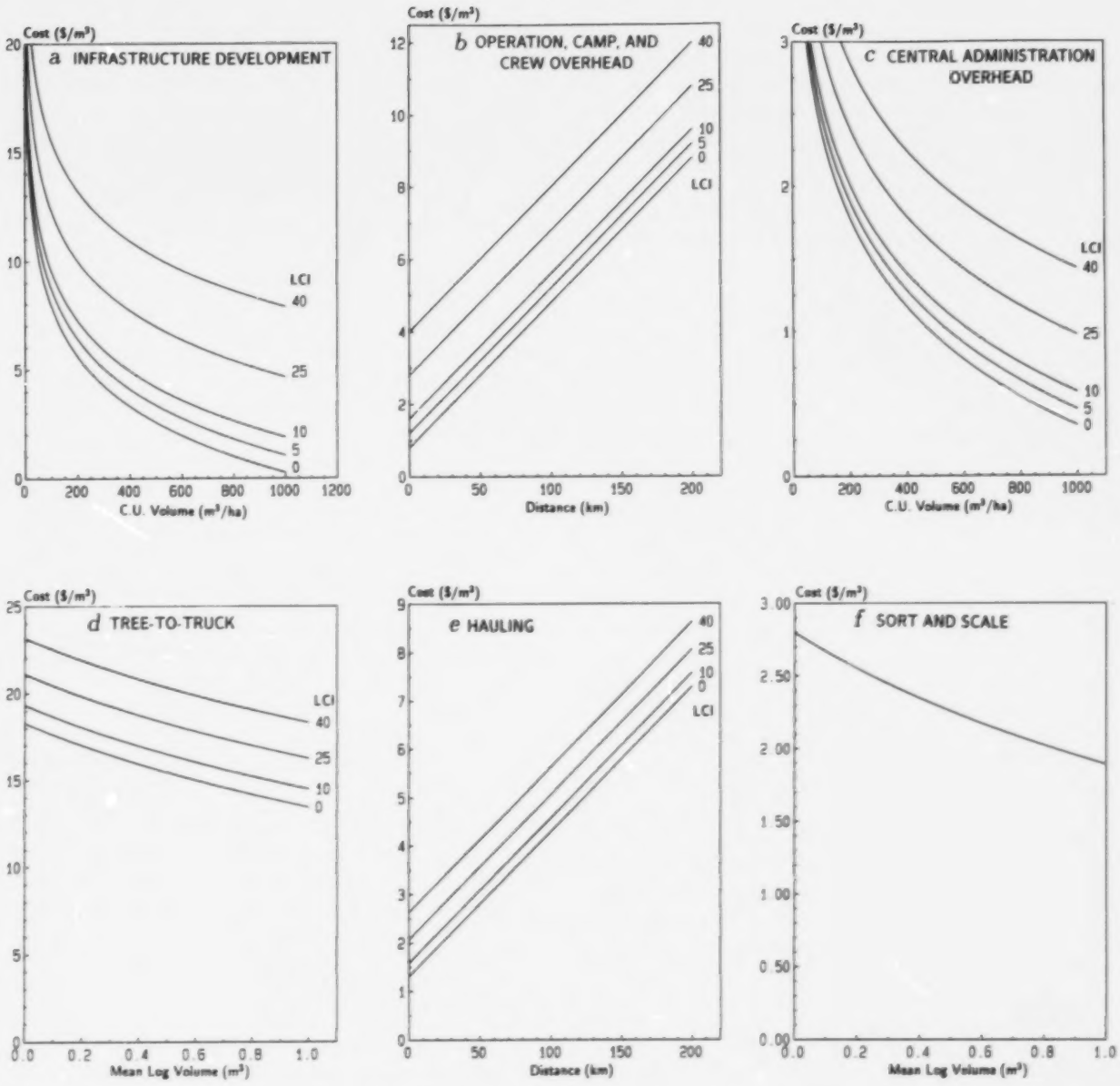


Fig. 13-11 Harvesting cost relationships for:
(a) infrastructure development,
(b) operation, camp, and crew overhead,
(c) central administration overhead,
(d) tree-to-truck operations,
(e) hauling distance, and,
(f) sorting and scaling.

Pruning Removing branches leads to the development of a shell of knot-free wood over the pruned length of the stem. Clear lumber cut from this section will bring a premium of about 300 percent. One or two lifts are permitted by FAN$Y. SAWSIM places an upper limit of 6.5 meters (21.3 feet) on the pruning height (i.e., a 20 foot log). Only one pruned log is permitted, although it may incorporate two lifts. Pruning cost functions are graphed in Figures 13-10e and 13-10f. The user must request the first and second lifts to remove branches to a height of 6 meters. That is, two 2 to 4 meter lifts are required to attain a height of 6 meters. The following tabulation assumes 400 trees are pruned per hectare at age 23 in an area with an LCI of 10:

1st lift	=	$310	(Figure 13-10e)
2nd lift	=	$650	(Figure 13-10f)
Total	=	$960	

Costs of $2.40 per tree ($960/400) appear to be a little low in light of information assembled since these functions were derived. Consequently, pruning is assigned a cost of $3.00 per tree in the demonstration runs. The second lift in the above example could be omitted or delayed until a later age, but may not appear alone. Note that the second and third prunings shown in Table 13-12a are redundant at present.

Fertilization Cost functions are provided with FAN$Y. However, this treatment will not be available for financial analyses until recent fertilization response data are incorporated into TASS.

Annual Overhead and Protection The administrative overhead cost of managing a hectare of forest land is in the neighborhood of $5 to $10 per year in addition to charges of $1.25 for protection provided by the Forest Service. A cost of $10 is assumed in the demonstration runs which accumulates to $600 over the payment period of 60 years illustrated in Table 13-15.

Harvesting Costs

Harvesting costs are itemized in Table 13-15. Costs relevant to a particular regime are provided by the user or calculated by the system using functions for infrastructure development (Figure 13-11a), operation, camp and crew overhead (Figure 13-11b), central administration overhead (Figure 13-11c), tree-to-truck operations (Figure 13-11d), hauling (Figure 13-11e), and sorting and scaling (Figure 13-11f). Important independent variables include LCI, volume harvested per hectare, average log volume, and hauling distance. This default information is based on functions fashioned after the appraisal methods developed by the Valuation Branch of the Ministry of Forests. No function is provided for water transport at present, although the total cost may be entered by the user. The coefficients of the equations which produce the default relationships displayed in Figure 13-11 may be changed by the user but not the functional relationships.

Manufacturing Costs

The manufacturing costs represent a hypothetical mill with a quad-band headrig, a double arbor gang saw, a board edger and the following throughput:

Production	=	90 million board foot per year
Average log length	=	15 feet (4.6 meters)
Average log volume	=	10 cubic feet (0.28 cubic meters)
Number of logs processed/shift	=	2900

Milling costs can be attributed to the handling and processing of individual logs or pieces of lumber in any proportion. At one extreme, all milling costs can be attributed to the log. The cost of milling a log is assumed to be relatively independent of its diameter over the range of sizes harvested in managed stands. Under these conditions, the total milling costs will increase in direct proportion to the number of logs harvested per hectare. At the other extreme, milling costs can be attributed to the number of pieces of lumber processed. Hence milling costs per log will increase in relation to log diameter while milling costs per cubic meter will decrease. FAN$Y permits a division of milling costs between logs and lumber in any proportion.

The default values in Table 13-15 which characterize the hypothetical mill used to demonstrate SYLVER are based on information reported by other Task Force studies for green and dry lumber. The demonstration runs assume that all costs are attributed to log processing (i.e., a ratio of 1.00). Users can manipulate these values to describe a particular mill. Costs per log and per piece of lumber are generated automatically on the basis of an eight hour day. Total manufacturing costs are derived from the number of logs and boards processed, and the corresponding piece rates.

Notice that three manufacturing costs in the economic data file (Table 13-15) must be increased if the lumber is dried. Drying costs are added automatically if the run parameter for lumber in Table 13-14 is set to dry (D).

Taxes

Annual taxes on forest property vary considerably in British Columbia. They are generally less than $1.00 per hectare ($0.30 - 0.90) in the interior, but higher on the coast where rates of $1.00 to 7.00 per hectare are common. A tax of $10.00 is assumed in the example in Table 13-15 which represents a highly productive site reasonably close to the mill. The next version of FAN$Y will include cost functions for an annual property tax, and a property yield tax based on operating difficulty (LCI), hauling distance and site index.

Log, Lumber and Chip Prices

The log prices (Table 13-15) for each grade of Douglas-fir (F) are the average of the Vancouver Log Market yearly average values for the period 1982 to 1986 (Average Log Price Report, Council of Forest Industries). Chip prices are from the same

Table 13-16. Lumber Premium Ratios

		Green Length Premium									Green Grade Premium						
		8	10	12	14	16	18	20	22	24	C1	C2	SS	1	2	3	Econ.
F	4	1.103	1.116	1.116	1.082	1.304	1.217	1.253	1.253	1.253	3.310	3.310	1.170	1.170	1.000	0.740	0.410
	6	1.169	1.135	1.271	1.139	1.348	1.287	1.316	1.399	1.464	3.230	3.230	1.180	1.340	1.000	0.700	0.400
	8	1.092	1.090	1.252	1.139	1.246	1.251	1.323	1.472	1.472	3.080	3.080	1.110	1.280	1.000	0.600	0.380
	10	0.867	0.871	1.069	1.099	1.060	1.009	0.984	1.105	1.097	2.860	2.860	1.020	1.180	1.000	0.560	0.360

		Dry Length Premium									Dry Grade Premium						
		8	10	12	14	16	18	20	22	24	C1	C2	SS	1	2	3	Econ.
F	4	1.103	1.116	1.116	1.082	1.304	1.217	1.253	1.253	1.253	3.140	3.140	1.250	1.060	1.000	0.720	0.320
	6	1.169	1.135	1.271	1.139	1.348	1.287	1.316	1.399	1.464	3.310	3.310	1.280	1.340	1.000	0.690	0.360
	8	1.092	1.090	1.252	1.139	1.246	1.251	1.323	1.472	1.472	3.310	3.310	1.280	1.280	1.000	0.640	0.360
	10	0.867	0.871	1.069	1.099	1.060	1.009	0.984	1.105	1.097	2.750	2.750	1.060	1.180	1.000	0.540	0.300

source. Both are in Canadian dollars. Lumber prices ($US/M fbm) are for random lengths, No. 2 and Better (average: 1981 - 1986) from information reported in Random Lengths for surfaced green dimension lumber. Premiums for length and grade are described in the next section.

Lumber Premiums

FAN$Y automatically applies price premiums for length and grade (Figure 13-9), relative to base prices for random lengths, and No.2 and Better grades, respectively.

Length

The lumber prices for random length lumber reported in Random Lengths were compared with the prices of lumber categorized by length (8 to 24 feet). These comparisons expressed as ratios provide length premiums for green and dry lumber (Table 13-16). The trend of change of these ratios over time was examined. As expected, the ratio varies over time but the relative position of the length premium for different dimensions (2 x 4, 2 x 6, etc.) is reasonably stable. The average length premium ratios for the period 1981 to 1986, which includes a full economic cycle, are incorporated into FAN$Y. The user can enter predicted prices ($US/M fbm) for random lengths No. 2 and Better, and have the price premiums for length added automatically before the lumber is priced. The length ratios are the same for green and dry lumber (Table 13-16). They can be changed by the user if desired.

Grade

Grade premiums are based on the procedure for lengths using prices reported by WWPA for coastal mills. That is, prices for No. 2 and Better were related as ratios to the prices for Clears, Select Structural, No. 1, No. 3 and Economy for the corresponding period (1981-1986). The ratios (Table 13-16) were found to be reasonably stable over the five year period, which showed major changes in prices within a grade. The grade premiums are incorporated into FAN$Y so that the user only has to specify the prices for No. 2 and Better lumber if the default values are acceptable. These ratios can be updated by the user. The premium for clear boards, for example, could be varied to evaluate the impact of pruning on financial return for a range of potential lumber prices.

Appraisal Data (Stumpage)

Stumpage is determined in accordance with the Ministry's "comparative value timber pricing system" which sets a total stumpage revenue goal for the province and then uses a formula to allocate the burden to the licensees. The essential components of this system are:

- *Minimum Rate* Lowest rate for which the Crown will sell a cubic meter of wood.
- *Base Rate* Rate set by the Ministry of Forests so as to generate the stumpage revenue desired. It is based on recent harvest data from all cutting authorities for the previous 12 months.
- *Value Index* Difference between appraised selling price and appraised operating costs on a particular site (cutting authority).
- *Mean Value Index* Average (volume-weighted) value index of all cutting authorities for the previous 12 months.
- *Indicated Rate (IR)* Rate calculated from the base rate and value index. That is,

  IR = Base Rate + (Value Index - Mean Value Index)

- *Silvicultural Allowance* Compensates for differences in treatment costs by district and silvicultural type. Silvicultural types and allowances, now under revision by the Ministry of Forests, will be replaced shortly.
- *Log Prices* Price of Douglas-fir logs on the Vancouver Log Market as determined by the Ministry of Forests for appraisal purposes.

Table 13-17a. Evaluation Report: Summary, Costs And Taxes

FAN$Y Evaluation: AC11PCL__
Page 1/2 Rotation: 60 years

1	DISCOUNTED REVENUES @ 4% [3 + 4 + 5][1]	4908.79
	DISCOUNTED COSTS @ 4% [1 + 2]	4336.21
	NET PRESENT VALUE (NPV) PER HA @ 4.0%	572.58
	INTERNAL RATE OF RETURN	4.952%
	RATIO OF NPV TO FORESTRY COSTS	0.63

OPERATING COSTS		Discounted	
Forestry			
Survey/Prescription	7.49	7.34	
Site Preparation	184.11	180.53	
Planting	432.62	424.22	
Land Rent (Annual)	151.12	59.14	
Annual Overhead & Protection	600.00	234.79	
Total	1375.34	906.02	
Harvesting @ age 60, 604.5 m^3/ha c.u.			
Infrastructure Development	2158.92	209.29	
Operation, Camp & Crew O/H	1692.53	164.08	
Central Admin. Overhead	621.93	60.29	
Tree-to-Truck	10551.83	1022.93	
Water Dump, Boom, Tow, Dewater	0.00	0.00	
Hauling	1501.50	145.56	
Sort & Scale	1473.79	142.87	
Total	18000.50	1745.02	
Manufacturing	11736.00	1137.72	
Total	31111.84	3788.76	[1]
TAXES			
Annual Property Tax	0.00	0.00	
Stumpage	5647.10	547.45	
Total	5647.10	547.45	[2]

1. [1] Operating Costs
   [2] Taxes
   [3] Revenue from the sale of logs
   [4] Revenue from the sale of lumber
   [5] Revenue from the sale of chips

- *Harvesting and Manufacturing Costs* Costs determined from FAN$Y's own models described earlier.

The appraisal system is applied separately for the coast and interior regions. The following hypothetical example from the coast applies to a regime evaluated in the Chilliwack Forest District. Supporting information is given in Tables 13-5, 13-12a and 13-17a. The relevant rates became effective October 1, 1987.

Minimum Rate	= $	0.25
Base Rate	= $	9.96
Mean Value Index (MVI)	= $	10.09

Revenue (logs)	= Volume (Table 13-12a)	x	Appraisal Price (Table 13-5)			
H-grade	= 112.5	x	62.52	=	$	7,033
I-grade	= 6.5	x	51.58	=		335
J-grade	= 466.5	x	35.51	=		16,565
X-grade	= 19.0	x	25.67	=		488
	604.5				= $	24,421

Harvest Cost (FAN$Y:Table 13-17a) = $ 18,001

Silvicultural Allowance per cubic metre (Chilliwack) = $ 1.78

Cost = Harvest Cost + (Silv. allowance x harvest vol.)
= $18,001 + ($1.78 x 604.5 m^3/ha) = $ 19,077

Value Index = (Revenue - Cost)/Volume
= ($ 24,421 - 19,077)/604.5 = $ 8.84

Indicated Rate = Base Rate + (Value Index - MVI)
= $ 9.96 + ($8.84 - 10.09) = $ 8.71

Stumpage Rate = Maximum of (Indicated & Minimum Rate
= Maximum ($8.71, 0.25) = $ 8.71

Stumpage Payable = Stumpage Rate x Log Volume
= $ 8.71 x 604.5 = $ 5,265

Prices and costs were assumed to remain constant for the 60 year rotation in this example (i.e., no cost/price trends). Otherwise, prices and cost would have to be altered. A base rate of $10.59 was used to calculate stumpage ($5,647) in Table 13-17a. This outdated value elevated the discounted stumpage and total discounted costs by $37, and depressed the net present value by the same amount.

Evaluation Reports

A single run with FAN$Y can generate evaluation reports (Figure 13-9) for combinations of up to 10 regime files, 5 managerial perspectives, 6 sites and 10 economic files for a total of 3000 reports! In practice, the user might select the 7 regime files shown in Figure 13-12 which incorporate one silvicultural treatment (i.e., plant 500 trees per hectare) and 7 harvest ages (i.e., 40, 50, 60, ..., 100) in combination with one managerial perspective (i.e., PCL: private operator logging Crown land and selling on the lumber market), one site index (i.e., unspecified: defaults to 35), one economic file (i.e., Vedder) with localized costs and prices, and the associated variables in the lower box. The input screen displayed by FAN$Y in Figure 13-12 will produce 7 reports.

The financial statement begins with a summary of the discounted revenues and costs, and the corresponding net present value followed by the internal rate of return and ratio of net present value to forestry costs (Table 13-17a). A detailed listing of the operating costs and taxes is appended. The sales value of logs, or lumber and chips (Table 13-17b) follows, showing both the undiscounted and discounted values. Sales revenue is derived from the sale of logs, or lumber and chips depending on the market option selected under the managerial perspective. The lumber market option also produces a table of lumber volumes by width and grade (Table 13-17b).

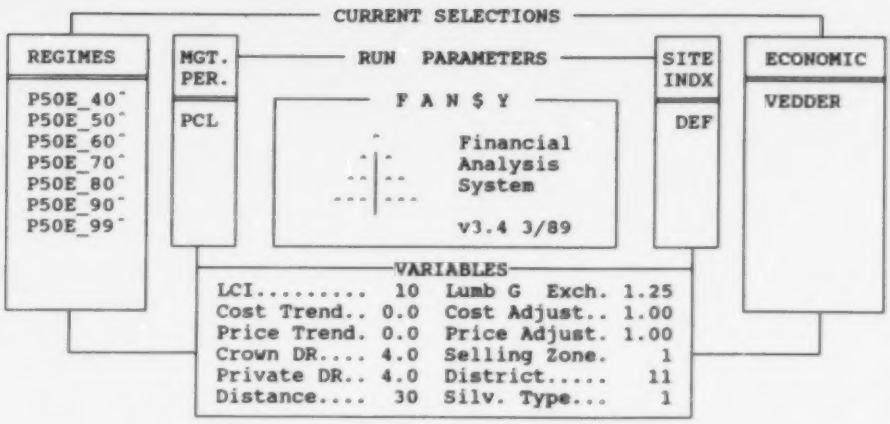


Fig. 13-12 User selected files and parameters displayed by FANSY

Table 13-17b. Evaluation Report: Lumber Value And Volume

FANSY Evaluation: AC11PCL__
Page 2/2

SALES VALUE-LOGS (not requested in this example) [3]

SALES VALUE - LUMBER

Fir	2x4"	2x6"	2x8"	2x10"
Clears	0.00	0.00	0.00	0.00
SS &1	6407.00	5844.71	4405.64	13427.06
2	2767.06	2322.36	1705.14	4211.00
3	940.96	731.63	487.31	1404.00
Econ.	347.94	278.35	205.72	601.73
TOTAL				46087.65

DISCOUNTED SALES VALUE - LUMBER

2x4"	2x6"	2x8"	2x10"	
0.00	0.00	0.00	0.00	
621.11	566.60	427.10	1301.66	
268.25	225.14	165.30	408.23	
91.22	70.93	47.24	136.11	
33.73	26.98	19.94	58.33	
DISCOUNTED			4467.86	[4]

SALES VALUE - CHIPS

Fir			
4548.34	0.00	0.00	0.00
TOTAL			4548.34

DISCOUNTED SALES VALUE - CHIPS

Fir				
440.93	0.00	0.00	0.00	
DISCOUNTED			440.93	[5]

VOLUME - LUMBER

Fir	2x4"	2x6"	2x8"	2x10"
Clears	0.00	0.00	0.00	0.00
SS &1	22361.00	17944.00	13798.00	42109.00
2	10762.00	8934.00	6309.00	14198.00
3	4967.00	4036.00	3017.00	8446.00
Econ.	3315.00	2687.00	2011.00	5631.00
TOTAL				170525.00

Table 13-18. Hypothetical Site: Plant 500 Trees and Harvest At Age 60

REGIME (e.g. file P50E_60^ selected by user)			
Species	Douglas-fir	Log Distribution (m^3/ha)	
Site Index	35m	H I J X	
Planting Density	500/ha	112.5 6.5 466.5 19.0	
Harvest Age	60 yrs	No. boards	10771/ha
Trees Harvested	438/ha	Lbr. Recov. Fac.	282 fbm/m^3
Volume (Close U)	604.5	Chip Recov. Fac.	90.97 BDU/ha
Logs Processed	1956/ha	Lumber distribution	Table 13-13
Decay, waste etc.	0 %		
RUN PARAMETERS (specified by user)			
Land Class Index	10	US Exchange Rate	1.25
Future Trend/yr:		Cost Adjustment	1.00
Costs	0.0 %	Price Adjustment	1.00
Prices	0.0 %	Selling Zone	1 (coast)
Discount Rate:		District	11 (Chilliwack)
Crown	4 %	Silviculture Type	1 (coast)
Private	4 %	Land Manager	Private
Hauling Distance	30 km	Land Owner	Crown
Lumber	Green	Analysis(Market)	Lumber
OPERATING COSTS (optionally specified by user)			
Forestry			
Survey/Prescription		$	7.49/ha
Site Preparation			184.11
Planting			432.62
Land Rent			0.25/m^3/ha/yr of MAI
Annual Overhead & Protection			10.00/ha/yr
Harvesting			18000.50 (Table 13-17a)
Manufacturing			
Cost/Log		$	6.00 (Table 13-15)
Number of Logs			1956.00 (Table 13-12a)
Total Cost		$	11736.00
Stumpage		$	5647.10 (Crown land: see text)
Taxes		$	10.00/ha/yr (private land)
SELLING PRICES & PREMIUMS (optionally specified by user)			
Lumber Prices: random lengths, #2 and better grade			
4"		$	168.30/fbm
6"			162.20
8"			168.20
10"			220.80
Premiums for length & grade			---- (see Table 13-16)
Chip prices		$	50.00/BDU

The net present value (NPV) is the single most relevant statistic generated by FAN$Y (Table 13-17a). A value of zero means that the target investment rate (discount rate) has been achieved. Values above zero represent returns on investments which exceed the target. However, the magnitude of the NPV and the apparent merit of a treatment from an investment perspective are very sensitive to the underlying assumptions. That is, two reasonable sets of assumptions could produce divergent NPVs.

The listing of discounted operating costs, taxes and sales revenue in each evaluation report (Table 13-17) helps the user assess the impact of itemized expenditures and revenues on NPV. For example, the contribution of each lumber category is displayed to show the effect of dimension and grade.

Demonstration: Establishing Silvicultural Priorities

The following simulated experiments illustrate methods of analyzing and interpreting data generated by SYLVER. The results are displayed solely to demonstrate the potential and limitations of the model. They must not affect management decisions or field procedures until the entire system is validated and customized to a particular site.

Planting Density

Consider a recently logged area of Crown land scheduled for site preparation and planting of coastal Douglas-fir. The forest manager may want to decrease the number of trees

Table 13-19a-f. Data For Evaluating Planting Density and Harvest Age

Planting Density	Harvest Age (years)						
	40	50	60	70	80	90	100
(a) Harvest Volume (m^3/ha): TASS: Figure 13-13							
1110	378	561	747	879	980	1035	1091
750	336	519	695	851	963	1028	1057
600	305	477	651	815	932	986	1084
500	279	439	605	760	888	990	1070
400	241	390	539	681	813	920	1025
300	203	331	462	587	698	801	898
(b) Lumber Volume (Mbf/ha): SAWSIM: Figure 13-14							
1110	91	143	198	241	278	306	324
750	83	134	188	238	277	306	325
600	77	125	178	231	272	302	326
500	71	119	171	218	262	299	327
400	63	106	154	200	241	277	312
300	52	91	133	171	207	239	268
(c) Lumber Recovery Factor (fbm/m^3): SAWSIM							
1110	240	255	265	274	284	294	299
750	248	259	270	280	287	298	304
600	254	263	274	283	291	300	304
500	253	271	282	287	295	302	306
400	261	272	285	294	297	301	304
300	254	274	287	292	296	299	299
(d) Log Value ($/ha): FAN$Y: Figure 13-15							
1110	12303	18446	25904	32419	38000	41810	44188
750	10605	16798	23714	31505	37001	41067	43001
600	9561	15729	23195	31112	36813	40811	44393
500	8629	15096	21860	28955	35209	40420	44842
400	7425	13056	19644	26414	33357	38719	42871
300	6257	11386	18005	24271	29525	34538	39411
(e) Lumber Value ($/ha): FAN$Y: Figure 13-15							
(No degrade for juvenile wood)							
1110	24232	38397	53574	65261	75440	83312	89907
750	22062	36211	50785	64663	75314	83307	89917
600	20591	33630	48155	62430	73759	82013	89931
500	18770	32077	46088	59196	71050	81345	89204
400	16812	28482	41582	54000	65430	75083	84642
300	13716	24340	34790	46405	56046	65005	73223
(Maximum degrade for juvenile wood)							
1110	16721	27844	40876	51598	61157	67945	73852
750	14970	25171	36991	49194	58898	66708	72309
600	13634	22876	34089	45886	56245	64307	71271
500	12116	20805	31761	42506	52520	61813	68815
400	10562	18006	27593	37273	46456	55013	62701
300	8476	15066	22931	30836	38254	45236	51863
(f) Chip Value ($/ha): FAN$Y: Figure 13-15							
1110	3542	4896	6181	6911	7316	7275	7441
750	3034	4427	5584	6482	7028	7037	6971
600	2680	3984	5126	6091	6641	6642	7119
500	2453	3519	4548	5548	6198	6581	6955
400	2030	3101	3990	4780	5589	6169	6737
300	1772	2612	3383	4163	4833	5458	6094

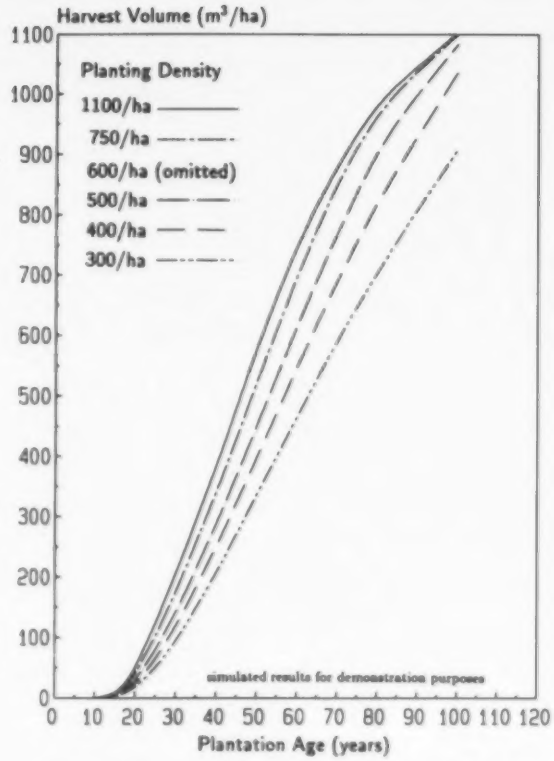


Fig. 13-13 Harvest volume versus plantation age by selected planting densities

planted as a means of reducing growing costs and increasing company profits. Assume current reforestation policy for highly productive sites calls for 1110 planted trees per hectare with harvesting scheduled for age 70. The manager might simulate planting densities of 1110, 750, 600, 500, 400 and 300 trees per hectare, and examine the potential for harvesting each density at decadal ages from 40 to 100 years. Figure 13-12 displays the summary screen of FAN$Y prior to the analysis of stands planted with 500 trees and harvested at the seven proposed ages. Input information processed by FAN$Y for the plantation harvested at age 60 is illustrated in Table 13-18. Table 13-17 shows the corresponding evaluation report. The following discussion of results covers the proposed range of planting densities and harvest ages.

Harvest Volume

The merchantable volume of standing timber (Table 13-19a) is displayed in Figure 13-13. The yield of young stands is proportional to the number of trees. However, differential mortality and other factors allow plantations of relatively wide spacing to close the gap and eventually surpass the yield of denser stands. The plantation with 300 trees will also conform to this pattern in time.

Table 13-19g-i. Data For Evaluating Planting Density and Harvest Age (continued)

Planting Density	Harvest Age (years)						
	40	50	60	70	80	90	100
(g) Net Present Value [NPV] ($/ha @ 4%): FAN$Y lumber (No degrade for juv. wood) & chips							
1110	-1835	-595	-169	-82	-188	-330	-466
750	-848	-40	229	197	5	-185	-374
600	-341	184	310	189	37	-130	-308
500	-116	493	573	315	108	-80	-287
400	177	574	571	388	107	-88	-269
300	-41	386	322	155	-5	-175	-338
(h) NPV/Forestry Cost Ratio (@ 4%): FAN$Y							
1110	-1.89	-0.59	-0.16	-0.08	-0.18	-0.32	-0.45
750	-0.93	-0.42	-0.24	0.20	0.01	-0.19	-0.38
600	-0.39	0.20	0.33	0.20	0.04	-0.14	-0.32
500	-0.14	0.56	0.63	0.34	0.12	-0.09	-0.31
400	0.22	0.68	0.66	0.44	0.12	-0.10	-0.30
300	-0.05	0.48	0.39	0.18	-0.01	-0.20	-0.39
(i) Internal Rate of Return (%): FAN$Y lumber (No degrade for juv. wood) & chips							
1110	---	1.9	3.6	3.9	3.7	3.6	3.3
750	-4.8	3.9	4.4	4.3	4.0	3.8	3.5
600	2.5	4.4	4.6	4.3	4.1	3.8	3.6
500	3.6	5.0	5.0	4.5	4.2	3.9	3.6
400	4.6	5.2	5.0	4.6	4.2	3.9	3.6
300	3.8	4.9	4.6	4.3	4.0	3.7	3.4

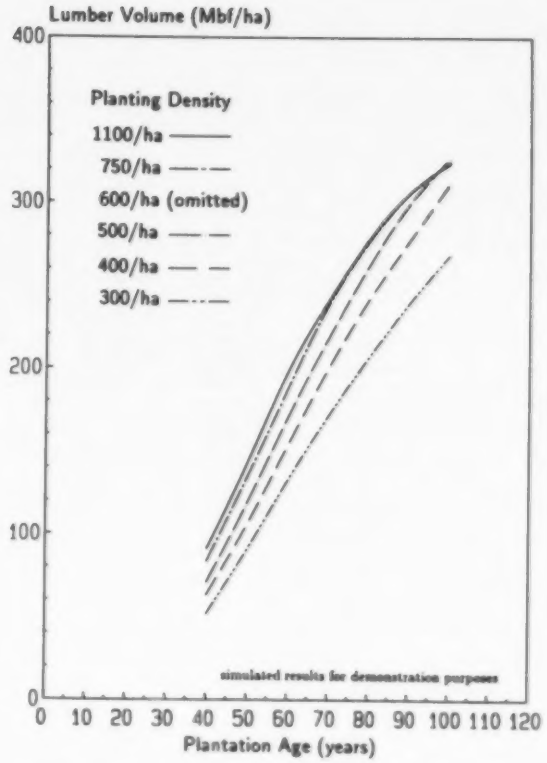


Fig. 13-14 Lumber value versus plantation age by selected planting densities

Table 13-20. Distribution of Log Volumes by Grade.

Planting Density (no./ha)	Harvest Age (years)	Log Grade H	I	J	X	Total Volume (m^3/ha)
		Volume (m^3/ha : %)				
300	40	1 (1)	2 (1)	176 (86)	24 (12)	203
	60	138 (30)	16 (4)	291 (63)	17 (3)	462
	80	253 (36)	100 (14)	333 (48)	12 (2)	698
	100	332 (37)	218 (34)	333 (37)	14 (2)	897
500	40	---	---	253 (91)	26 (9)	279
	60	113 (19)	6 (1)	467 (77)	19 (3)	605
	80	280 (31)	34 (4)	557 (63)	17 (2)	888
	100	417 (39)	80 (8)	558 (52)	15 (1)	1070
750	40	---	---	319 (95)	17 (5)	336
	60	66 (10)	---	615 (88)	14 (2)	695
	80	271 (28)	10 (1)	667 (69)	15 (2)	963
	100	386 (36)	27 (3)	631 (60)	13 (1)	1057
1110	40	15 (4)	---	346 (92)	17 (4)	378
	60	89 (12)	---	643 (86)	15 (2)	747
	80	291 (30)	---	677 (69)	12 (1)	980
	100	406 (37)	---	674 (62)	10 (1)	1091

Log Volume

The predicted volume of logs harvested per hectare is identical to the standing volume shown in Table 13-19a since decay, waste and breakage are assumed to be negligible in trees from second-growth forests. The distribution of volume by log grade is listed in Table 13-20 for a cross-section of planting densities and potential harvest ages. J-grade logs are most prevalent at a particular age because the minimum permissible diameter is only 10 centimeters as opposed to 30 and 38 centimeters for H- and I- grade logs, respectively (Table 13-5). The proportion of J-logs decreases as tree size responds to increasing age and wide initial spacing. That is, trees of relatively large dimensions produce a greater proportion of 5-m logs which qualify for the higher grades. Notice that the proportion of H- and I-grade logs increases as stands age. The decline in I-grade logs towards higher densities may reflect a decrease in knot size which permits the logs to qualify for the H-grade. Short logs of low value accumulate in the X grade. Their distribution bears little relationship to age or density because they originate from the uppermost part of the stem. The proportion of volume by grade shown in Table 13-20 conforms reasonably well with the results of Chapter 7 considering that the latter study combined logs from stands covering a range of ages and densities.

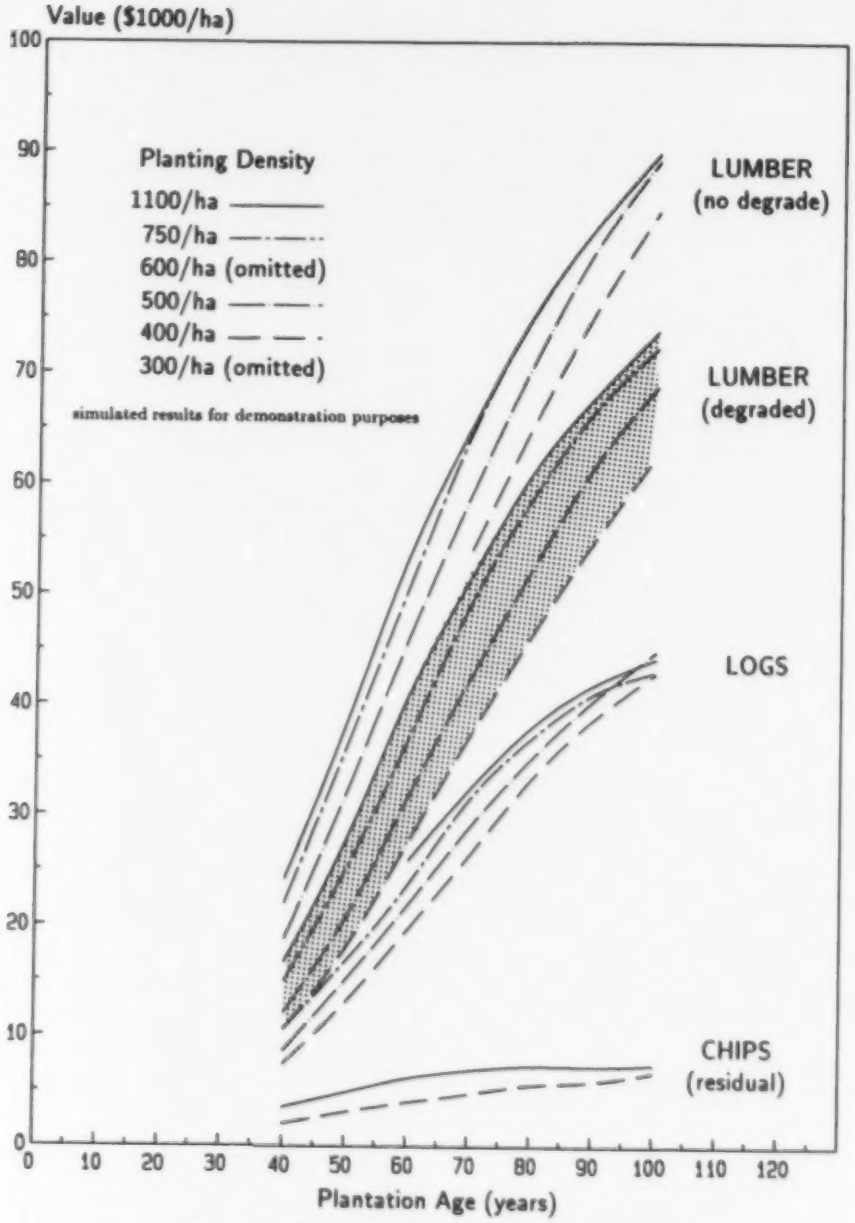


Fig. 13-15 Product value versus plantation age by selected planting densities

Lumber Volume and Recovery

The effect of espacement on lumber volume (Table 13-19b; Figure 13-14) imitates that of standing volume. Lumber recovery factors (Table 13-19c) calculated from Tables 13-19a and 13-19b improve as trees increase in age and size. Notice that trees from open-grown stands have relatively high lumber recovery at 40 years because of their size, but the advantage slowly declines as the stands age. Chapter 7 reported comparable recovery factors of 265 to 283 board feet per cubic meter for stands which varied in age from 42 to 62 years (Chapter 1) assuming four years were required to reach breast height after planting. The combined sources of information, including observed stocking densities, imply that establishment density likely ranged from 400 to 1110 trees per hectare.

Product Value

The value of end-products (Tables 13-19d to 13-19f) realized from each planting density and potential harvest age is illustrated in Figure 13-15 for lumber (with and without degrade for juvenile wood), logs and residual chips. Degrading lumber for juvenile wood content lowers its value by 20 to 30 percent. These estimates may be overly pessimistic because they assume that all boards in the affected visual grades (Table 13-7) are shifted to less demanding classes. The introduction of machine stress rating systems, in place of visual grading procedures, would reduce the number of boards degraded and the overall impact of the variable strength properties of juvenile wood. Logs provide less revenue because they are relatively unmanufactured, and of much less value per cubic meter than lumber.

Net Present Value

NPV in Table 13-19g is the difference between the sales revenues and costs including stumpage (Table 13-17a) after discounting all values to the time of planting. The impact of planting density, harvest age and juvenile wood content is displayed graphically in Figure 13-16. Stands established with 400 to 500 trees and harvested 50 to 60 years later provide higher returns than alternative regimes when the conventional visual grading procedures are applied. Recognition of juvenile wood properties reduces NPV substantially, expands the range of optimum planting densities (500-750 trees per hectare) and delays harvesting until age 90. However, the negative impact of juvenile wood displayed in Figure 13-16 will likely be countered in part by current and future technology. Table 13-19g and Figure 13-16 analyze silvicultural practices from the perspective of a private company managing Crown land as opposed to private forests. The latter situation is represented by the lowermost curve in Figure 13-17 for a plantation of 500 trees. NPVs are considerably higher ($275 at 55 years) because the tax on private property is much less than stumpage paid for timber harvested on Crown land. However, the optimum planting density and harvest age, in terms of NPV, does not change appreciably. The returns from pruning shown in Figure 13-17 are discussed later.

The interpretation of NPV is straightforward. Any investment opportunity that yields a NPV of zero or more dollars will generate income at the discount rate (e.g., 4%) or above. Consequently, the manager would likely pursue all opportunities with a positive NPV if funds are unlimited. Where projects are mutually exclusive, the manager would choose the project with the highest NPV. The incorporation of budget constraints is discussed in the next section.

Ratio of Net Present Value to Forestry Costs

This ratio of NPV to forestry costs measures the return relative to expenditures on forest management. The example in Table 13-17a has a ratio of 0.63 ($572.58/$906.02) which means that each discounted dollar spent on forestry returns $0.63 (discounted) more than would be realized by investing it at 4 percent. The manager would favor investments with the highest ratio of NPV to forestry costs when faced with budget constraints (Table 13-19h). Budget constraints occur when there are insufficient funds to invest in all projects with an NPV equal to or greater than zero. From this perspective, plantations with 400 trees will outperform all other densities if harvested between age 50 and 60. NPV/cost ratios can also evaluate the contribution of optional treatments. The incremental benefits of pruning are analyzed later.

Internal Rate of Return

The internal rate of return (IRR) is the discount rate that equates costs to revenues as illustrated in Table 13-17a which shows a rate of 4.952 percent. The NPV of $572.58 in the upper part of Table 13-17a represents excess return relative to the target rate of 4 percent. Using a discount rate of 4.952 percent in the analysis in place of 4 percent would yield an NPV of zero. Notice that each regime with a positive NPV in Table 13-19g also has an internal rate of return greater than 4 percent (Table 13-19i). The relative merits of treatments based on IRR may not be consistent with results using other investment criteria because of differences in the implied underlying assumptions, particularly if the time periods are not comparable. For example, stands planted with 500 trees and harvested at age 50 or 60 years generate the same IRR of 5 percent in Table 13-19i. The corresponding ratios of NPV to forestry costs (0.56 versus 0.63) in Table 13-19h are considerably different because each method of analysis imposes different assumptions for the 10 year period following cutting at age 50. IRR can be used when funds are limited although economists generally prefer the ratio of NPV to forestry costs. Mishan (1975) gives a comprehensive discussion of these investment criteria.

Mean Annual Increment

Harvest volumes can be sustained at the highest level over a series of rotations by selecting the planting density and age that achieve the maximum mean annual increment (MAI). For

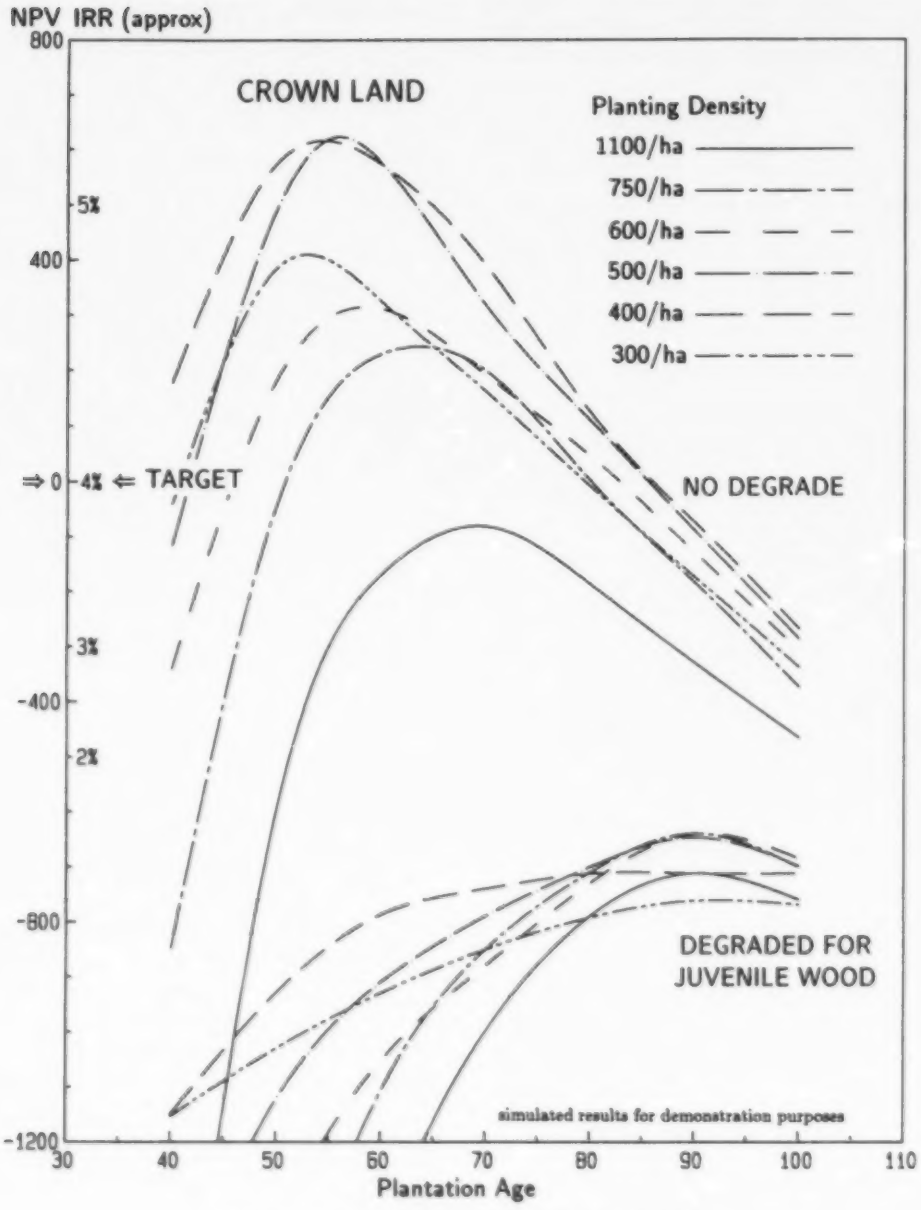


Fig. 13-16 Net present value (NPV: $/ha) and internal rate of return (IRR: %/ha) versus plantation age by planting density on Crown land

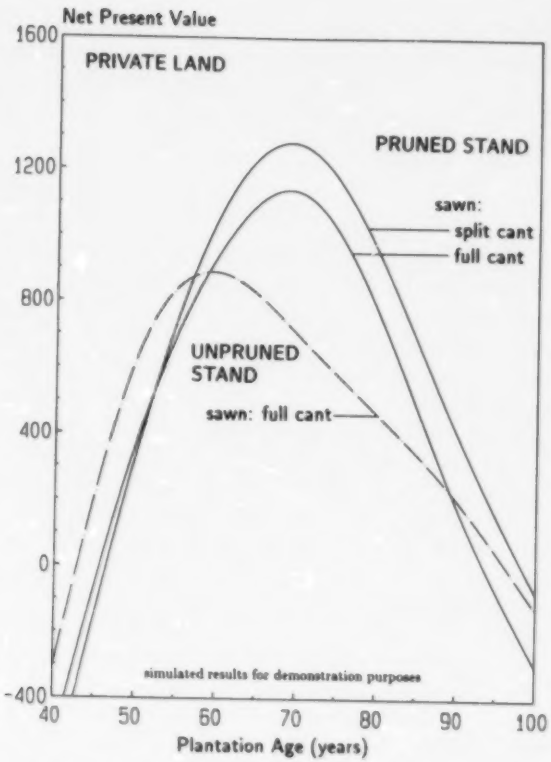


Fig. 13-17 Net present value ($/ha) of pruned and unpruned stands versus plantation age for a planting density of 500 stems per hectare on private land

Table 13-21. Incremental Analysis of Pruning on Private Land

Investment Criteria	Harvest Age (years)						
	40	50	60	70	80	90	100
Plant 500 Trees/Ha and Prune @ Age 23							
NPV($)[1]	-678	332	1049	1277	953	402	-80
Cost ($)	1410	1441	1464	1478	1487	1490	1492
NPV/Cost	-0.48	0.23	0.72	0.86	0.64	0.27	-0.05
Plant 500 Trees/Ha and Omit Pruning							
NPV($)[1]	-306	623	885	699	459	202	-128
Cost($)	853	884	906	921	930	933	935
NPV/Cost	-0.36	0.70	0.98	0.76	0.49	0.22	-0.14
Differential Contribution of Pruning							
NPV($)[1]	-372	-291	164	578	494	200	48
Cost($)	557	557	557	557	557	557	557
NPV/Cost	-0.67	-0.52	0.29	1.04	0.89	0.36	0.09
NPV($)[1]	392	(1277 - 885)					
Cost($)	572	(1478 - 906)					
NPV/Cost	0.68	(392 / 572)					

1. Based on split-cant sawing.

example, dividing each entry in Table 13-19a by the corresponding age gives a maximum value of 12.6 cubic meters per year at age 70 when 1110 trees are planted. The same analysis gives different results when applied to other measures of productivity as shown below:

MAI Indicator	Density	Harvest Age
Volume		
standing/logs	1110	70
lumber	1110	75
Value (revenue)		
lumber	1110	75
logs	1110	80
NPV		
no degrade	400-500	55
degraded	500-750	90

The optimum planting density and harvest age depends on an organization's objective. A policy that strives to maximize the merchantable volume of standing timber, or logs, encourages relatively high planting densities (e.g., 1110 trees per hectare). Emphasizing lumber volume has a similar effect, except that the harvest age is delayed by 5 years to capture improvements in lumber recovery as trees and logs achieve larger dimensions. The MAI of lumber value gives identical results. Log value tends to extend the cutting age. This may reflect the relationship between log diameter and price. The attractiveness of high establishment density and long rotations vanishes when planting and carrying costs are incorporated into the analysis through NPV which directs the manager to plant 400 to 500 trees and harvest at age 55. An analysis of the NPV of lumber degraded for juvenile wood recommends increases in the planting density and harvest age. Both actions reduce the proportion of undesirable juvenile wood in trees.

Pruning

The results from the simulated experiment with different planting densities may encourage the forester in this hypothetical example to look for other opportunities to increase net revenue. Pruning is a likely choice because clear lumber currently commands a premium in excess of 300 percent relative to the price of the No. 2 and Better grade category. We may assume that pruned plantations established with 500 trees on private land are of immediate interest. However, the pruning cost functions shown in the economic file do not agree with the company's experience of $1.00 and $2.00 per tree for lifts 1 and 2, respectively, for 23 year old

stands pruned to a height of 6.5 meters. This amounts to $3.00 per tree or $1350 per hectare, assuming 450 trees survive to age 23. To remedy the situation, the manager recalls the economic file and enters $450 and $900 in place of the pruning cost functions for the two lifts. The results are summarized in Figure 13-17 along with comparable information from the untreated companion stand growing on private land. Pruning increases the NPV by $250 and delays the optimal harvest age by about 10 years, assuming conventional full-cant sawing is employed in both cases. Split-cant sawing of pruned logs further elevates the NPV by $150. This method of sawing reduces lumber recovery by about 1 percent but increases the yield of clear lumber by 6 percent because logs are positioned so that boards are more closely aligned with the knot-free shell. Clear lumber produced by pruning and split-cant sawing accounts for 14 percent of the total volume, and 33 percent of the value.

Treatments other than pruning (such as juvenile spacing and fertilization) will also have an impact on the financial analysis to a greater or lesser degree. They will be evaluated in future trials with SYLVER.

Incremental Analysis

The manager investigating treatment opportunities may want to compare the incremental benefits of treatments that enhance the quantity or quality of wood produced by a base regime. For example, what is the return on each dollar spent pruning a young stand planted with 500 trees? This treatment is particularly interesting because the analysis of incremental return must accommodate different harvest ages.

The NPV displayed in Figure 13-17 is the combined return from planting and pruning on private land. The contribution of pruning (split-cant sawing) can be isolated by comparing the two alternative management options (i.e., planting 500 trees per hectare and pruning at age 23, versus planting alone). Table 13- 21 shows the NPV, forestry costs and corresponding ratio for each option, followed by the differential contribution of pruning in terms of NPV and costs. The ratio of NPV to forestry costs is calculated from these differences in the third section of Table 13-21. The positive values suggest that the incremental benefits of pruning begin to accrue by age 60 and peak about 10 years later when the NPV and ratio of NPV to forestry costs reach $578 and 1.04, respectively. However, this analysis assumes that both management options incorporate the same harvest age. A close examination of each shows that the investment criteria culminate close to 60 years for planting alone, and about 70 years for the combined treatment. The incremental contribution of pruning at optimal harvest ages is given at the bottom of Table 13-21. The pruning component of the treatment regime has an NPV of $392, and each dollar spent on pruning yields $0.68 more than would be earned by investing it at 4 percent. Note that NPV expresses net return which is the difference between revenues and costs, including forestry costs. If the latter cost had not been removed, the ratio calculated at the bottom of Table 13-21 would increase from 0.68 to 1.68. This means that $1.68 of discounted revenue is returned for every dollar invested in pruning at 4 percent.

Sensitivity Analysis

The preceding demonstrations show that net present value and rotation age are sensitive to planting density, pruning and juvenile wood content. However, there are many other variables in FAN$Y that affect the outcome of the financial analysis. These include other regime variables (site quality), run parameters (operating difficulty [LCI], cost/price trends, discount rate, hauling distance, kiln drying and exchange rate), operating costs (forestry, harvesting, manufacturing, stumpage and taxes), and product prices. The user needs to be aware of the variables that can alter the results through relatively small changes in magnitude. Site index, for example, can be tested by changing its current value of 35 meters incrementally to evaluate the impact of site quality on the culmination of NPV and associated rotation age. The value of all other independent variables should be standardized at values such as those given in Table 13-18. Each sensitivity trial in the following analysis is viewed separately from the perspective of a company logging Crown land and private land. Some scenarios might give unrealistic results because arbitrary conditions may be created by restraining variables that are closely linked (such as property tax and site quality). The stand with 500 trees per hectare serves as the base case in the following analysis.

Site Productivity

In this trial, site index is decremented in steps of 5 meters from 45 to 25 meters. Figure 13-18a shows a steep decline in NPV ($2400 to -$600), and increase in harvest age (46 to 80 years) on Crown land. NPV is even more sensitive to site quality on private land, although the length of the rotation is less affected. The crossing of the curves is an anomaly that would not likely appear if property taxes, currently held constant at $10 per hectare per year, were tied to site index. Prorating taxes from $15 on site 45 to $5 on site 25 causes the lines to merge below site 30. The curves cross when the discounted tax payments exceed the stumpage paid for Crown timber.

Land Class Index (LCI)

This run parameter of operating difficulty, previously set at 10 (Table 13-18), is allowed to range from 0 to 30 in Figure 13-18b. NPV is highly sensitive to LCI while the harvest age is quite stable. The latter increases slightly on Crown land. Notice that it is better for industry to manage Crown land than its own land when the LCIs exceed 20, because the tax on private property is greater than the stumpage paid for public timber! Taxes are not adjusted for LCI, unlike stumpage rates.

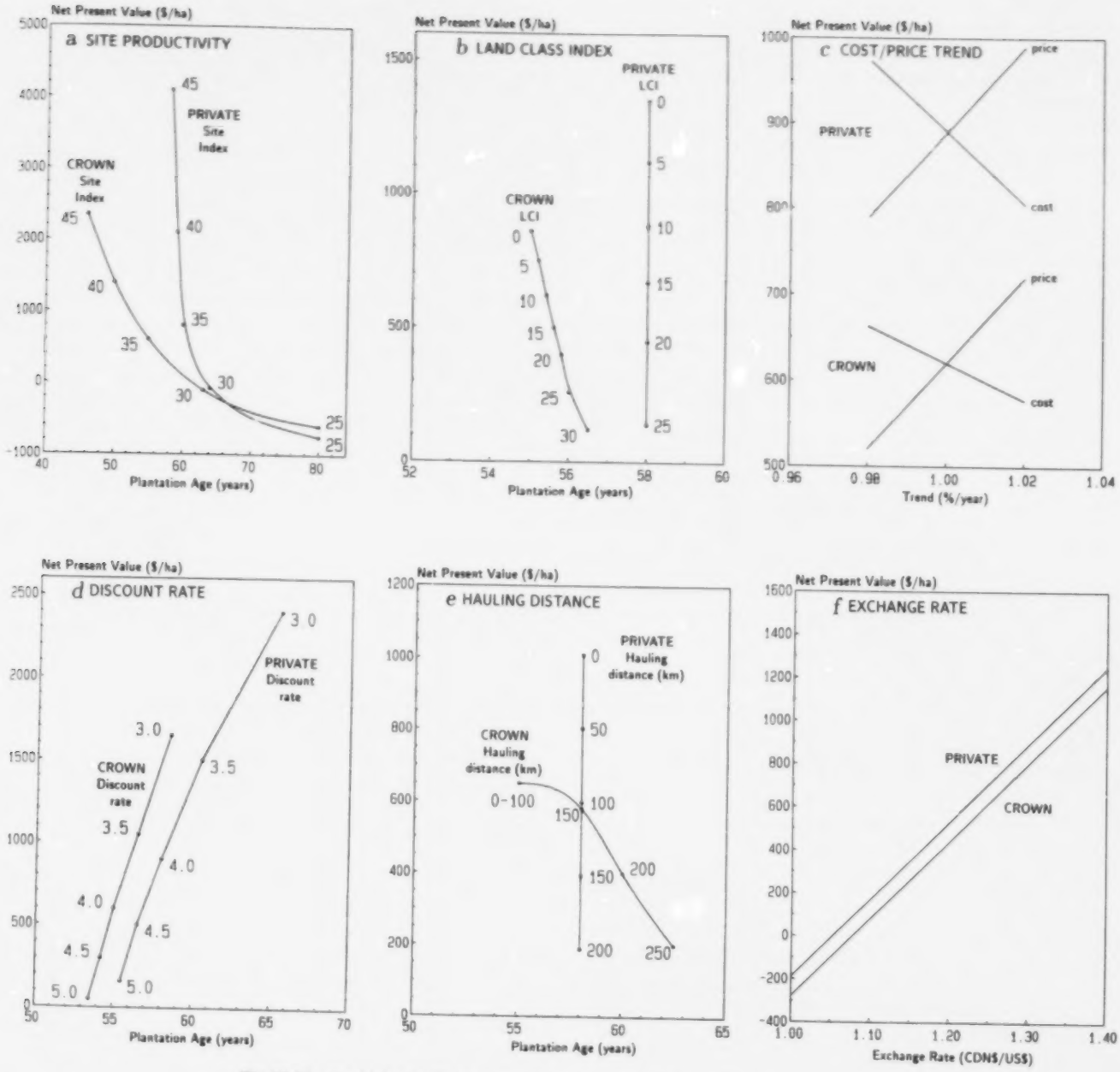


Fig. 13-18 Sensitivity of NPV and harvest age to:
(a) site productivity,
(b) land class index,
(c) cost and price trends,
(d) discount rate,
(e) hauling distance, and
(f) exchange rate for both private and Crown land operations

Table 13-22. Effect of Costs on Net Present Value at Age 60.

CROWN LAND	Net Present Value of 500 Planted Trees ($/ha)							
	0	200	400	(573)[1]	600	800	1000	
	Cost on Crown Land							Increment
Planting	1017	813	609	(433)	405	201	-3	$ 204/ha
Overhead[2]	34.40	25.90	17.40	(10.00)	8.90	0.30	-8.30	8.50/ha
Hauling[3]	21.30	17.90	14.50	(2.50)[3]	--	--	--	3.40/m^3
Stumpage[4]	20.40	17.00	13.60	(10.59)	10.20	6.80	3.30[4]	3.40/m^3

PRIVATE LAND	Net Present Value of 500 Planted Trees ($/ha)							
	0	200	400	600	800	(885)[1]	1000	
	Cost on Private Land							Increment
Planting	1335	1131	927	723	519	(433)	315	$ 204/ha
Overhead[2]	47.70	39.20	30.70	22.20	13.60	(10.00)	5.10	8.50/ha
Hauling[3]	17.60	14.20	10.80	7.40	3.90	(2.50)	0.50	3.40/m^3
Taxes[5]	47.70	39.20	30.70	22.20	13.60	(10.00)	5.10	8.50/ha

1. Actual values from the planting density experiment.
2. Annual overhead and protection.
3. Hauling costs are offset by reductions in stumpage until the minimum rate ($0.25/m^3) is imposed coincidentally with a hauling cost of $11.50/m^3. That is, any hauling cost under $11.50/m^3 will generate a net present value of $573/m^3.
4. Minimum stumpage sets a lower limit of $1.50/m^3 on the base rate, and a corresponding upper limit of $1105/ha on NPV in this example.
5. Annual cost.

Cost and Price Trends

Figure 13-18c shows that annual changes in costs and prices have a substantial effect on NPV, considering the scale only ranges from -2 percent (0.98) to +2 percent (1.02). Harvest ages are not affected. Notice that the slopes of the price lines are identical on Crown and private land while the cost functions are not. NPV is less sensitive to cost trends on Crown land because stumpage decreases in response to an increase in harvesting costs.

Discount Rate

Figure 13-18d shows a reduction in NPV and rotation age on both public and private land as the discount rate increases from 3 to 5 percent. This is no surprise since carrying costs rise exponentially.

Hauling Distance

Increasing the hauling distance on private land decreases NPV without altering the time of harvest (Figure 13-18e). The situation on Crown land is more complex. Neither variable is affected by hauling distances up to 100 kilometers because transportation costs are deducted from stumpage. Offsetting costs continue until minimum stumpage is imposed. Additional hauling costs must be absorbed by the operator, causing a reduction in NPV and a lengthening of the rotation. Note that hauling costs contribute to the determination of stumpage for a particular site but do not affect the base rate for the region.

Drying

Kiln drying lumber from stands established with 500 trees per hectare increases the selling price of lumber by $30 per thousand board feet at a cost of just under $10 per thousand. This boosts the NPV by about $700 assuming no degrade due to drying. If degrade is included, the benefits from drying ($450) are somewhat lower. The change in NPV is identical on Crown and private land as shown below:

	Crown			Private		
	Dry	Green	Gain	Dry	Green	Gain
No drying degrade	1325	(625)	700	1600	(900)	700
Drying degrade	1075	(625)	450	1350	(900)	450

The rotation age is stable on each tenure.

Exchange Rate

Figure 13-18f shows that NPVs of public and private timber are equally sensitive to the exchange rate for the United States dollar through its impact on the value of lumber in Canadian dollars. Harvest ages are not affected.

Planting Costs

Table 13-22 shows the relationship between planting cost per hectare and NPV for stands established with 500 trees. Rotation length is kept at 60 years for convenience in this and later analyses because it is not affected by planting costs. Planting 500 trees costs $433 and produces a NPV of $573 on Crown land in the current analysis. Increasing planting costs

to $609 decreases the NPV to $400 (Table 13-22). An expenditure of $813 reduces NPV to $200. That is, a change of $204 in the planting cost alters NPV by $200. The direct relationship between cost and NPV also applies to survey, site preparation, and all other one-time costs incurred at the time of stand establishment. These initial costs only benefit from a discount period of 0.5 years unlike harvest costs which are discounted over the entire rotation. The relationship between planting cost and NPV is similar on private land (lower part of Table 13-22) although shifted due to the higher NPV ($885) at age 60.

Annual Overhead and Protection Costs

The sensitivity of NPV to annual overhead and protection costs is analyzed in the same manner as planting costs. These costs (currently $10 per hectare per year) differ in that they are expended annually for 60 years. A change of $8.50 per year is required to alter NPV by $200 (Table 13-22) on both Crown and private land.

Hauling Costs

Hauling costs, like other harvesting and manufacturing expenditures incurred at the end of the rotation, have relatively little impact on NPV because discounting at 4 percent for 60 years reduces every dollar to about 10 cents. On Crown land, hauling costs (currently $2.50 per cubic meter) are offset by reductions in stumpage (currently $10.59 per cubic meter) until the minimum stumpage rate ($0.25 per cubic meter) is imposed coincidentally with a hauling cost of $11.50 per cubic meter (Table 13-22). Further increments of $3.40 per cubic meter cause a corresponding reduction of $200 in NPV. The sensitivity of NPV to hauling costs is similar on private land although stumpage is not a factor.

Stumpage and Taxes

Stumpage (base rate) on Crown land has a similar impact on NPV as hauling costs because both are incurred at time of harvest (Table 13-22). Taxes on private land are identical to annual overhead and protection costs in terms of amount ($10 per hectare per year), payment (annual) and relationship to NPV (Table 13-22).

Recommendations and Conclusions

SYLVER was conceived and designed as a silvicultural tool for forest managers responsible for evaluating the impact of cultural practices and environmental variables on standing yield, product recovery and financial return. Initial validation shows that it has successfully integrated the results of other Task Force projects into a system that is sensitive to environmental variables, silvicultural practices, wood properties, product quality, financial return and management opportunities. The striking increase in the net present value of pruned stands illustrates the dynamics of financial yield, and the insight that SYLVER can provide when adequately validated.

Reviewers of interim copies of FAN$Y recognized that its financial summaries could be misinterpreted and applied incorrectly if distributed to foresters with good intentions but no experience. Consequently, the Task Force recommends that a formal training program be prepared and made available to the personnel of member organizations planning to evaluate or implement the system.

The Task Force encourages its members to test FAN$Y rigorously, and assess its performance in relation to their practical experience in sectors simulated by SYLVER. Users are also requested to recommend future directions for system development. Current plans call for additional silvicultural treatments (e.g., juvenile spacing, fertilization, and commercial thinning), processes such as stress grading, and economic analyses that will incorporate social benefits. All suggestions will be evaluated and incorporated into the next version of SYLVER where practical.

References

Barrett, J.D. and R.M. Kellogg. 1986. Lumber quality from second-growth managed forests. In: A Technical Workshop: Juvenile wood - What does it mean to forest management and forest products? Proceedings 47309. Forest Products Research Society, Madison, WI. p.51-71.

Bruce, D. 1981. Consistent height-growth and growth-rate estimates for remeasured plots. Forest Sci. 27:711-725.

Goudie, J.W. 1980. Yield tables for managed stands of lodgepole pine in northern Idaho and southeastern British Columbia. M. Sc. thesis, Univ. of Idaho, Moscow, ID. 111p.

Hay-Roe, R. 1988. Papertree Letter. March 1. Vancouver, BC.

Middleton, G.R. and B.D. Munro. 1985. Product outturn values for British Columbia coastal log grades: an information report. Canadian Forestry Service Contract Report No. 40-012-424. Forintek Canada Corp., Vancouver, BC. 22p.

Mitchell, K.J. 1969. Simulation of the Growth of Even-aged Stands of White Spruce. Bulletin No. 75. Yale University, School of Forestry. New Haven, CT. 48p.

Mitchell, K.J. 1975. Dynamics and simulated yield of Douglas-fir. Forest Sci. Mono. 17. 39p.

Mitchell, K.J. and I.R. Cameron. 1985. Managed stand yield tables for coastal Douglas-fir: initial density and precommercial thinning. Ministry of Forests, Research Branch, Land Management Report No. 31. Victoria, BC. 69p.

Mitchell, K.J. and K.R. Polsson. 1988. Site index curves and tables for British Columbia: coastal species. Ministry of Forests, Research Branch, Forest Resource Development Agreement, Report 037. Victoria, BC. 29p.

Mishan, E.J. 1975. Cost-Benefit Analysis. George Allen and Unwin, London. 454p.

Random Lengths Publications. 1976-1986. Random Lengths: Lumber price guide: Prices to wholesalers. Framing Lumber. Eugene, OR.

Western Wood Products Association. 1976-1986. Monthly F.O.B. price summary past sales - key items basis: Coast Mills. Report 12. Portland, OR.

Acknowledgements

Work on this project undertaken by the Research Branch was funded through the Ministry of Forests by the direct delivery component of the Canada/British Columbia Forest Resource Development Agreement - a five year (1985-90) $300 million program cost-shared equally by the federal and provincial governments.

The authors gratefully acknowledge the support of J. Goudie, W. Howard, D. Coffey, D. Geils and other Ministry staff; G. Brunette of Forintek Canada Corp.; D. Ormerod and S. Wilson of Sylvametrics Consulting, H. Leach of Halco Software Systems Ltd., R. Macdonald of RamSoft Systems Ltd., and the industrial and Forest Service personnel who tested the system.

PART VI: Conclusions and Recommendations

The results of this study show that, largely due to the high proportion of juvenile wood, second-growth coastal Douglas-fir harvested in 50 to 70 years will have physical, mechanical and chemical properties substantially different from the old-growth resource harvested today. Juvenile wood volume may be as high as 50 percent of total volume at these rotation ages. Juvenile wood, which in this study material comprised on average the first 23 rings from the pith, has an average relative density of 0.46. The average stemwood relative density of the study trees is 0.48 while the best estimate of average old-growth relative density is about 0.51 to 0.52.

A great deal of tree-to-tree variation in longitudinal shrinkage exists, but on average the longitudinal shrinkage of the innermost juvenile wood is more than twice that of mature wood. No sharp distinction can be observed between juvenile and mature wood based on longitudinal shrinkage, but it appears that the most serious levels are generally confined within the first five rings from the pith. In contrast, the fiber length increased dramatically from between 1.0 and 2.0 millimeters at the pith to between 3.0 and 4.0 millimeters in the mature wood. These mature wood values were not attained for approximately 30 rings from the pith, so it can be anticipated that the average fiber length of short rotations stands will be substantially less than that of old-growth material.

In terms of chemical properties, lignin content of juvenile wood is higher than that of mature wood, but a comparison of the mean second-growth values with those available for old-growth shows that they are not appreciably different. A similar comparison shows total extractive content of second-growth is lower than that of old-growth.

More than half of the total log volume in the study trees fall into the J grade category; a small good quality sawlog. The lumber recovery factor of 256 fbm per cubic meter for these J logs was nearly identical to that for old-growth J logs. The lumber recovery of approximately 300 fbm per cubic meter obtained for I, H, and C grade logs is somewhat higher than averages obtained for old-growth of the corresponding grades, while the recovery factors for X and Y grade logs (the lowest grades) are substantially lower than those obtained for old-growth. These lower recovery factors are due to differences in average log size. The yield of lumber graded No. 2 and Better was 5 to 10 percent lower for second-growth log grades compared to old- growth grades except in Y grade logs where the value for old-growth was 3 percent lower than for second-growth.

The conversion of second-growth Douglas-fir will yield no clear grades without pruning. Clear grades in old-growth have comprised 9 percent of the volume and 21 percent of its value as recently as 1975. Approximately 35 percent of the lumber sawn in this study was graded as Select Structural. The two major reasons for lumber being graded lower than this were knots (29.1 percent) and wane (28.6 percent).

The factor primarily determining lumber value is tree and log size. Grades No. 2 and Better accounted for a relatively constant average of 82 percent of all lumber. Increased yields of Select Structural that were obtained as log diameter increased were largely at the expense of reductions in the yield of No. 1 and No. 2 lumber. Clearly, differences in lumber value related to log quality depend on a premium price for Select Structural. Without this premium for grade the effect that log size has on value would become even more important, because premium prices are usually paid for the widest lumber widths.

Although knots were a major determinant of visual lumber grade there is no direct linear relationship between knot size and visual grade. This results from the fact that an acceptable knot size for a given lumber grade is defined by the size of the lumber piece and by the location of the knot within the piece.

Lumber grade and value considerations of second-growth material will have to include the impact of juvenile wood on lumber drying and strength characteristics. Warp, particularly twist, was a major drying degrade factor with a strong tendency for warp to increase with increasing proportion of juvenile wood. In Select Structural lumber containing 90 to 100 percent juvenile wood, over 20 percent of the lumber had twist in excess of the grade limit causing a drop in grade to either 2, 3 or Economy.

Of greater concern is the magnitude of potential grade and value reduction resulting from the reduced strength and stiffness of lumber with high proportions of juvenile wood. For example, Select Structural lumber containing 90 to 100 percent juvenile wood from butt and middle logs has a stiffness (Modulus of Elasticity) approximately 80 percent of that from mature wood and would not meet the design code requirements. These results do not reflect the design values that could currently be assigned to random samples of visually graded lumber as typically marketed in British Columbia.

Rather, they bring industry's attention to a potential value problem should there be a significant change in log sorting strategies, proportion of second-growth being harvested or a change in forest management strategy that increases the production of low density lumber.

There is a substantial proportion of the lumber from second-growth trees with high strength and stiffness properties that are not recognizable by means of visual grading. By contrast, machine stiffness rating systems provide a direct method of assessing the structural performance capability of each piece of lumber. In a similar sense, conventional kiln-drying schedules and practices may result in appreciable drying degrade in second-growth Douglas-fir lumber containing a high proportion of juvenile wood. Methods have been developed elsewhere in the world to deal with similar drying problems and these should be examined to develop a cost-effective means of reducing degrade losses in this material.

Perhaps one of the greatest values in the information obtained in this study is the recognition of potential quality problems so that methods can be developed to deal with them effectively before this type of wood becomes a significant component of the harvested coastal Douglas-fir resource. The results should suggest ways in which second-growth can be converted, graded or marketed in order to realize its highest potential value.

If the second-growth coastal Douglas-fir resource or sawmill residuals from that resource are converted to kraft or refiner mechanical pulp certain observations can be made on the characteristics of those pulps based on the results of this study. Yields of both bleachable-grade and linerboard grade kraft pulps were consistently lower for juvenile wood relative to mature wood while the yields of top wood was intermediate. Juvenile wood cooked faster than mature wood. Bleachable-grade kraft pulps from juvenile wood and top wood formed denser sheets than those from mature wood at any level of beating. They also were smoother and less porous to air. Presumably due to an improved interfiber bonding, the juvenile wood and top wood pulps had higher tensile and burst strength, a greater stretch and stress-strain factor than those from mature wood. On the other hand the juvenile wood and top wood pulps were substantially lower in tear strength than the mature wood pulps. The wide ranging properties of bleachable-grade kraft pulps made from the different components from the second-growth Douglas-fir resource were predictable on the basis of wood or chip density, fiber length and fiber coarseness.

An increase in the proportion of juvenile wood will adversely affect the tear index of kraft pulps of coastal Douglas-fir to a point where they are more comparable with the tear strength of other Canadian softwoods. This drop in tear is offset to some degree by increased tensile strength and sheet density. In short, the future resource can be expected to produce a more balanced kraft pulp. It appears that there is the potential for an increased range of properties from kraft pulps of second-growth Douglas-fir which offers a broader range of utilization options. Other softwoods may not be capable of providing a comparable range in properties.

Fibers from mature wood refiner mechanical pulps were longer and coarser than those from juvenile wood and top wood pulps. As a result mature wood pulps were stronger in both tensile and tearing strength.

The optical properties of mature wood pulps, however, were inferior, as shown by decreased printing opacity and scattering coefficients compared to those of juvenile and top wood pulps. The lower density of wood of the second-growth resource will require a higher specific energy than used at present to reach a given pulp freeness.

It has been found that the properties of refiner mechanical pulps can be predicted and explained primarily on the basis of fiber length, fiber strength and Klason lignin content of the wood. Wood density is also important, but unlike the models developed for kraft pulps, plays a less dominant role. Consideration of available options for utilization of second-growth Douglas-fir refiner mechanical pulps suggests that there is good potential for the production of mechanical pulps with a distinctive range of properties.

The second major contribution of this study has been the development of a model called SYLVER which can relate silvicultural strategies to standing yield, product recovery and financial return. Initial validation shows that SYLVER has successfully integrated the results of other Task Force studies into a system sensitive to environmental variables, silvicultural practices, wood properties, product quality, financial return and management opportunities.

The model suggests an increased return on investment through the establishment of coastal Douglas-fir plantations at stocking densities of 400 to 500 trees per hectare as opposed to the current practice of 900 trees per hectare. On highly productive sites the highest return would be realized with a harvest rotation of 50 to 60 years when conventional visual grading procedures are applied.

Recognition of the potential end-product quality problems resulting from the high proportion of juvenile wood resulting from this strategy results in a marked reduction in the net present value, expands the range of optimum planting densities (500-750 trees per hectare) and delays harvesting until age 90. Defining the magnitude of these effects provides the forest industry with some sense of the potential value losses against which the investments in either technological or biological solutions to the problem can be compared. The optimum planting density and harvest age depends on an organization's objective.

A policy that strives to maximize the merchantable volume of standing timber, or logs, encourages relatively high planting densities (1110 trees per hectare). Emphasizing lumber value

has a similar effect. The attractiveness of high establishment density and long rotations vanishes when planting and carrying costs are incorporated into the analysis through net present value.

The results from the simulated experiment with different planting densities may encourage the forest planner to look for other opportunities to increase net revenue. Pruning is a likely choice with clear lumber presently demanding a price premium in excess of 300 percent relative to No. 2 and Better, and the realization that short rotation unpruned stands will produce essentially no clear lumber. The model suggests that pruning will increase the net present value by as much as $400. It is predicted that a single lift pruning to 6.5 meters at age 20 would result in clear lumber accounting for 14 percent of the volume and 33 percent of the lumber value. This striking increase in the net present value of pruned stands illustrates the dynamics of financial yield and the insight that SYLVER can provide when adequately validated.

Integrated efforts like the Douglas-fir Task Force provide a means of developing a knowledge of the wood characteristics that determine end-product value. This is essential information for tree improvement planners who may want to consider the potential they have to offset some of the negative wood quality features expected in the managed second-growth resource. Models like SYLVER offer the potential of evaluating the effects of genetic manipulations of the wood characteristics which are critical in determining end-product value. The model should be able to consider the costs of genetic manipulation and trait measurement in tree improvement programs so that assessments of overall financial return of potential investments can be made in terms of net present value. These options are just beginning to be explored but with further refinement of the model the potential of this application is very real.

The Task Force recognizes that certain assumptions are made in carrying out these analyses with which not all potential users agree with. These assumptions have been described in Chapter 13 and for the most part users of FAN$Y have considerable control over the assumptions when developing their own financial evaluations. It may be considered a bold assumption that structural lumber will still be produced from stands of coastal Douglas-fir at the end of the next rotation. The demonstration runs of the model have assumed there will still be a premium in the market place for clear lumber and that the use of wood as a structural material will continue to be economical. The form of structural members may change, but it is reasonable to assume that the value of the raw material will remain related to its inherent structural performance potential.

If Canada's forest industry is to remain competitive on the world market we must maintain a high quality resource which will permit the greatest flexibility in the manufacture of a variety of high quality value added products.

The Task Force encourages users to test FAN$Y rigorously, and assess its performance in relation to their practical experience in sectors simulated by SYLVER.

APPENDIX I: Douglas-Fir Log Grades[1]

5.45 Fir and Pine Grades

With the exception that pine has no peeler grades these two genera are graded the same. The grades apply to all species of pine found in the province. See section 4.17.

5.451 No. 1 Peeler Fir, Grade Code A

5.4511 *Grade Rule*

Fine grained logs 5.2 m or more in length and 38 cm or more in radius where at least 80% of the gross scale will cut out on a rotary lathe into veneer and at least 35% of the veneer will be clear and of uniform colour.

5.4512 *Log Requirements to Make the Grade*

(a) No conk, conk stain or pocket rot is permitted.

(b) There must be no fewer than 6 annual rings in each 2 cm of diameter.

(c) Logs must have at least 50% of the visible surface clear with only a few well spaced knots or knot indications no more than 4 cm in diameter permitted on the upper 25% of each side and only one knot or knot indication no more than 4 cm in diameter permitted in the next 25% of each side.

(d) Maximum twist permitted over 30 cm in length is 8% of the radius up to a maximum deviation of 6 cm.

(e) Butt rot must not be present in logs less than 8 m in length.

(f) The diameter of butt rot in logs 8 m to 10.2 m in length must not exceed 33% of the measured butt diameter after excluding flare.

(g) The diameter of butt rot in logs 10.4 m or over in length must not exceed 50% of the measured butt diameter after excluding flare.

(h) Butt star checks must not be longer than half the top diameter of the log.

(i) No more than one heart check or split which must not affect the outer 25% of the diameter is permitted.

(j) Only small pitch pockets ranging in numbers per end from four for logs 38 cm in radius to seven for logs 76 cm or over in radius are permitted.

(k) One tight partial ring shake which does not extend around half the circumference of the ring and does not have checks at right angles to the shake, or a full ring shake with a diameter less than 33% of the diameter of the log is permitted.

(l) No sap rot or sun checks are allowed in logs less than 25 centimetres in radius. Logs 25 centimetres in radius and greater can exhibit sap rot or sun checks to a depth of 4 percent of the top diameter of the log. The maximum depth of sap rot or sun checks shall not exceed 5 centimetres.

(m) Sweep is permitted providing the log meets the grade rule.

(n) Bucking breaks, splits and broken ends are allowed provided the defect can be eliminated in a length equal to the top diameter.

(o) Burls are permitted to the extent of one medium or large size burl for every 2.6 m of log length.

5.452 No. 2 Peeler Fir, Grade Code B

5.4521 *Grade Rule*

Fine grained logs 5.2 m or more in length and 30 cm or more in radius where at least 80% of the gross scale will cut out on a rotary lathe into veneer.

5.4522 *Log Requirements to Make the Grade*

(a) No conk, conk stain or pocket rot is permitted.

(b) There must be no fewer than 6 annual rings in each 2 cm of diameter.

---

[1] British Columbia Ministry of Forests. 1980, Forest Service Scaling Manual. (Revised March 1983). British Columbia Ministry of Forests, Victoria. 264 p.

(c) Logs 30 cm or over in radius must have one 2.6 m butt block free of knots or knot indications.

(d) Logs 38 cm or over in radius must have one 2.6 m butt block free of knots.

(e) No knots over 4 cm are permitted and knots or knot indications 4 cm or less in diameter must be well spaced.

(f) Maximum twist permitted over 30 cm of length is 14% of the radius up to a maximum deviation of 8 cm.

(g) Other defects are permitted as listed for No. 1 Peeler Fir. See section 5.4512 items (e) to (m).

5.453 No. 3 Peeler Fir, Grade Code C

5.4531 *Grade Rule*

Logs 5.2 m or more in length and 19 cm or more in radius where at least 80% of the gross scale will cut out on a rotary lathe into veneer.

5.4532 *Log Requirements to Make the Grade*

(a) No conk, conk stain or pocket rot is permitted.

(b) There must be no fewer than 5 annual rings in each 2 cm of diameter.

(c) No knots over 4 cm in diameter are permitted and knots 4 cm or less in diameter must be well spaced.

(d) Maximum twist permitted over 30 cm of length is 14% of the radius up to a maximum deviation of 8 cm.

(e) Other defects are permitted as listed for No. 1 Peeler Fir. See section 5.4512 items (e) to (m).

5.454 No. 1 Lumber Fir and Pine, Grade Code D

5.4541 *Grade Rule*

Logs 5 m or more in length and 38 cm or more in radius where at least 75% of the gross scale will cut out merchantable or better grade of lumber and at least 50% of the lumber will be clear.

5.4542 *Log Requirements to Make the Grade*

(a) No conk, conk stain or pocket rot is permitted.

(b) There must be no fewer than 6 annual rings in each 2 cm of diameter.

(c) Logs must have at least 90% of the visible surface clear with only a few well spaced knots or knot indications no more than 4 cm in diameter permitted on the upper 10% of two sides or the upper 20% of one side.

(d) Maximum twist permitted over 30 cm in length is 8% of the radius up to a maximum deviation of 6 cm.

(e) Only small pitch pockets ranging in numbers per end from three for logs 38 cm in radius to six for logs 76 cm or over in radius are permitted.

(f) No ring shakes are permitted in that part of the log between 8 cm and 20 cm of the bark.

(g) A ring shake within 8 cm of the bark is only permitted if within that part of the log inside the shake there is sufficient wood free of knots or other defects to make the grade rule.

(h) Insect or worm holes other than ambrosia must not penetrate beyond the sap wood.

(i) Ambrosia, butt rot, burls, checks, crook, heart rot, ring shake, sap rot, shatter, splits, sweeps, or other defects are permitted providing the portion of the log free from these defects is sufficient to meet the grade rule.

5.455 No. 2 Sawlog Fir and Pine, Grade Code H

5.4551 *Grade Rule*

Logs 5 m or more in length that are:

(a) 15 cm or more in radius where at least 75% of the gross scale will cut out lumber, or

(b) 25 cm or more in radius where at least 50% of the gross scale will cut out lumber,

and at least 65% of the lumber will be merchantable or better.

5.4552 *Log Requirements to Make the Grade*

(a) There must be no fewer than 3 annual rings in each 2 cm of diameter.

(b) On logs 15 cm to 18 cm in radius there must be no more than well spaced knots up to 5 cm in diameter over the upper 33% of the visible surface, or reasonably well spaced knots up to 2 cm in diameter over all the visible surface.

(c) On logs 19 cm to 24 cm in radius there must be no more than well spaced knots up to 5 cm in diameter over 50% of the visible surface, or reasonably well spaced knots up to 4 cm in diameter over all the visible surface.

(d) On logs 25 cm or over in radius there must be no more than occasional knots up to 8 cm in diameter over 50% of the visible surface, or reasonably well spaced knots up to 5 cm in diameter over 67% of the visible surface or reasonably well spaced knots up to 4 cm in diameter over all the visible surface.

(e) Maximum twist permitted over 30 cm in length is 14% of the radius up to a maximum deviation of 8 cm.

(f) Insect or worm holes other than ambrosia must not penetrate beyond the sap wood.

(g) Ambrosia, burls, butt rot, checks, conk, conk stain, crook, heart rot, oversized knots, pitch pockets, pocket rot, ring shake, sap rot, shatter, splits, sweep or other defects are permitted providing the portion of log free from these defects is sufficient to meet the grade rule.

5.456 No. 3 Sawlog Fir and Pine, Grade Code I

5.4561 *Grade Rule*

Logs that are:

(a) 3.8 m or more in length and:

(i) 19 cm or more in radius where at least 75% of the gross scale will cut out lumber, or

(ii) 25 cm or more in radius where at least 50% of the gross scale will cut out lumber

and at least 50% of the lumber will be merchantable or better, or

(b) 5 m or more in length and 19 cm to 24 cm in radius where at least 50% of the gross scale will cut out lumber and 65% of the lumber will be merchantable or better.

5.4562 *Log Requirements to Make the Grade*

(a) by log radii, maximum knot size diameters which should not prevent the manufacture of the lumber requirements of the grade are:

Log Radius	Knot Size Diameter
19 - 24 cm	8 cm
25 - 37 cm	9 cm
38+ cm	10 cm

(b) Maximum twist permitted over 30 cm of length is 20% of the radius up to a maximum deviation of 9 cm.

(c) Ambrosia, bunch knots, burls, butt rot, checks, conk, conk stain, crook, heart rot, insect holes, loose knots, oversized knots, pitch pockets, pocket rot, ring shake, rotten knots, sap rot, shatter, splits, sweep, or other defects are permitted providing the portion of the log free from these defects is sufficient to meet the grade rule.

5.457 No. 4 Sawlog Fir and Pine, Grade Code J

5.4571 *Grade Rule*

Logs 5 m or more in length and 5 cm to 18 cm in radius where at least 75% of the gross scale will cut out lumber and at least 50% of the lumber will be merchantable or better.

5.4572 *Log Requirements to Make the Grade*

(a) Knots with diameters up to a maximum diameter of 6 cm should not prevent the manufacture of the lumber requirements of the grade, with the provision for oversize knots as noted in (c) below.

(b) Maximum twist permitted over 30 cm of length is 20% of the radius.

(c) Ambrosia, bunch knots, burls, butt rot, checks, conk, conk stain, crook, heart rot, insect holes, loose knots, oversize knots, pitch pockets, pocket rot, ring shake, rotten knots, sap rot, shatter, splits, sweep, or other defects are permitted providing the portion of the log free from these defects is sufficient to meet the grade rule.

5.458 No. 5 Utility Fir and Pine, Grade Code X

5.4581 *Grade Rule*

Logs 2.6 m or more in length and 5 cm or more in radius where at least 33.3% of the gross scale will cut out lumber and at least 50% of the lumber will be merchantable or better.

5.4582 *Log Requirements to Make the Grade*

(a) By log radii, maximum knot size which should not prevent the manufacture of the lumber requirements of the grade are:

Log Radius	Knot Size Diameter
18 cm, or under	10 cm
19 - 37 cm	13 cm
38 cm, or over	15 cm

(b) Maximum twist permitted over 30 cm of length is 26% of the radius up to a maximum deviation of 13 cm.

(c) Ambrosia, bunch knots, butt rot, conk, conk stain, crook, heart rot, insect holes, loose knots, oversize knots, pocket rot, ring shake, rotten knots, sap rot, shatter, splits, sweep, or other defects are permitted providing the portion of the log free from these defects is sufficient to meet the grade rule.

5.459 No. 6 Chipper Fir and Pine, Grade Code Y

5.4591 *Grade Rule*

Logs that are lower in grade than utility but are better quality than firmwood rejects.